EEL 4915 SENIOR DESIGN II

DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

UNIVERSITY OF CENTRAL FLORIDA

Senior Design II Term Paper

ACDC – A Helping Hand – Group A

Akash Jinandra – EE & CpE

Carlos Cuesta – EE & CpE

Devin Defond – EE

Chang Ching Wu – EE

Table of Contents

1. Executive Summary

The motivation of the project came from watching the movie surrogate. We noticed that the surrogate robot can go through many hazardous conditions and environments that humans cannot. Obviously we do not have the technical knowledge and resources to create these full scale robots with that much detail. What if instead we could control the robots with our actual movements instead of using a joystick or controller? Also we could not make a full scale robot let alone control it during our 1 semester building phase of senior design. So we thought of the minimum viable product that would be the most useful. We settled on a robotic arm. This is arguable one of the most useful parts of the human body, the dexterity of 5 fingers and the 3 degrees of freedom of a whole arm.

We decided the control will have a form factor similar to a sleeve, which will contain sensors on each finger, wrist, and major joint of the arm. The finger sensors will be using accurate flex sensors that change resistance as the finger flexes. The sensors will also be used on the elbow as well as the palm and the wrist. These sensors will add gripping capability. Gyroscope sensor is what we plan to use on the wrist to add degrees of freedom. All of these sensors will be sewn into a fabric glove. The sensors will be wire onto a microcontroller, MCU, such as Arduino or a MSP430 board. We are still deciding whether the communication will be local or will be over the internet

The Arm itself will be mounted on a table from the elbow. It will be able to move up and down and rotate 360 degrees horizontally. We plan to use six micro-servo motors for the fingers and the pisiform, to give each fingers and the pisiform the ability to open and close with the similar dexterity as an animatronics' hand. Two standard-servo motors will be use to give the palm of the hand the ability to fold up and down and swing left to right, by pushing/ pulling moment arm attached to the wrist at different combinations. For the elbow, we plan on using a stepper motor for the beneficial factor of high torque and higher precision of micro-stepping. But, since there is no feedback for a stepper motor, a feedback sensor, hall-effect encoder, should be attach to the rotary axis of the elbow to allow accurate measurement for feedback.

The applications of this project are limitless. We can attach this arm to a robot and use it for bomb disposal. The bomb technician will not have to learn a new system and can use his instincts without hesitation. We can also use it in a situation where there is radiation and our arm has to operate things that humans usually operate, such as controls, switches. A more domesticated version of this would be mounted on a desk. This can be used for support for IT. For instance, an elderly person who can’t type for themselves, or don’t know where to click the mouse. Or maybe helping engineers with circuits, if they don’t know how to connect something properly, a seasoned engineer can help them with ease.

2. Project Description

To get the project started, it must be first known why we began this project in the first place. It also must be known how we are going to approach this project as well as state any standards, constraints, and requirements for this project for a better understanding of the project parameters. In the following sections, a brief overview of the project will be mentioned, followed by how the project will be implemented in the next sections.

2.1. Motivation

The motivation of the project came from watching the movie surrogate. We noticed that the surrogate robot can go through many hazardous conditions and environments that humans cannot. Obviously we do not have the technical knowledge and resources to create these full scale robots with that much detail. What if instead we could control the robots with our actual movements instead of using a joystick or controller? Also we could not make a full scale robot let alone control it during our 1 semester building phase of senior design. So we thought of the minimum viable product that would be the most useful. We settled on a robotic arm. This is arguable one of the most useful parts of the human body, the dexterity of 5 fingers and the 3 degrees of freedom of a whole arm.

2.2. Project Specifications

An overall view of the project, including the arm and the sleeve will be laid out here. The block diagrams showing system level functionality will also be shown and explained.

2.2.1. Overall Block Diagram

The overall block diagram shows the general idea and implementation of the project where a user wears a sleeve, which has sensors tracking movement that communicates with a mechanical arm to mimic the movements of the user. Figure 2.2.1-1 shows the overall block diagram of the entire project.

Figure 2.2.1-1: Overall Block Diagram of System

2.2.1.1. Hardware

Hardware is essential to the project as it allows a physical entity to show work through research and design. The overall block diagrams for the hardware will be shown and explained.

2.2.1.1.1. Hardware of Arm

The communication module will be how the arm and sleeve communicate. The MCU will be used to control the motor controller and servo controllers, while getting feedback from the motor controller to determine and verify location of the arm. The servo and motor controllers control their respective servos and motors for the arm. The power block would provide power to the MCU, motor and servo controllers through AC to DC conversion and DC-DC regulation.

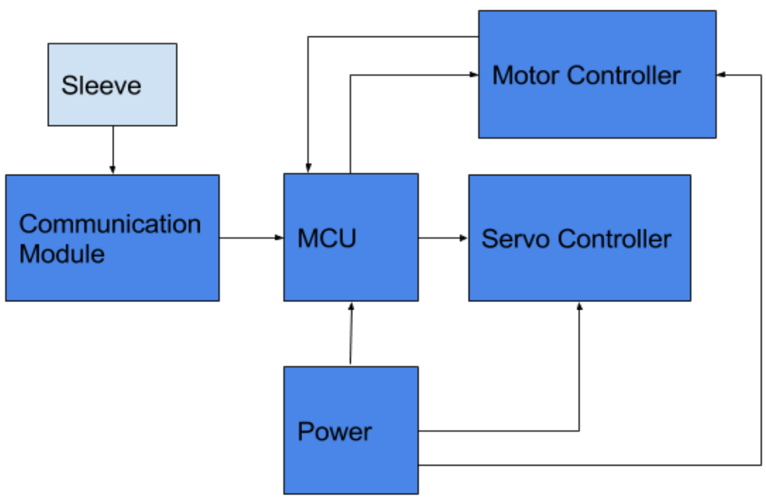


Figure 2.2.1.1.1-1: Overall Block Diagram of Arm Hardware

Within the servo control block, the servo controller with be in charge of handling the servos associated with the wrist, forearm, and hand, which itself includes the finger, thumb, and pisiform joints. Within the motor control block, the motor controller is in charge of handling the elbow motor and its respective sensors, which will relay information regarding in position and movement back to the MCU. The power block diagram is broken into its steps in its AC to DC conversion process.

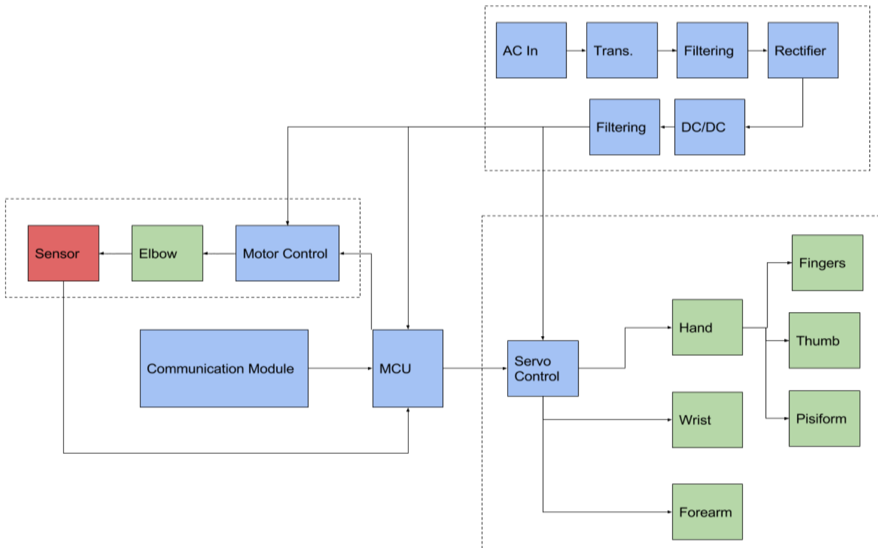


Figure 2.2.1.1.1-2: In-depth Block Diagram of Arm Hardware

2.2.1.1.2. Hardware of Sleeve

The human input block represents the human wearing the sleeve itself to be monitored by the sensors. The sensors will provide information regarding the human arm's location and position to provide to the MCU. The MCU will be in charge of processing all data received by the sensors on the sleeve, which will be sent to the communication module to be sent to the arm via some sort of wireless communication. The power module is self-explanatory as it provides DC power through a battery and DC-DC conversion to the over modules of the sleeve, including the communication module, the sensors and MCU.

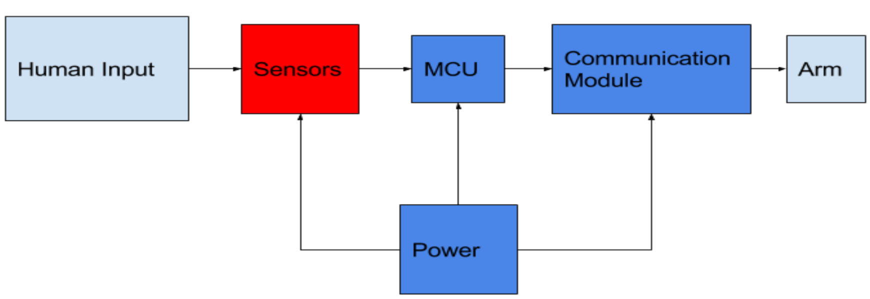


Figure 2.2.1.1.2-1: Overall Block Diagram of Sleeve Hardware

2.2.1.2. Software

Software allows us to easily execute complex programs. Software also helps to tie the hardware pieces together. Hardware and software go hand in hand. The overall block diagrams for the software are shown here.

2.2.1.2.1. Software of Arm

As shown in Figure 2.2.1.2.1-1, the software block diagram for the arm. We read in our signals using our communication module, most likely an RF Device using SPI. It will then set up all the functions and start the main loop where it calls the other functions. These include the servo and motor functions which control the fingers, wrist, palm, and elbow.

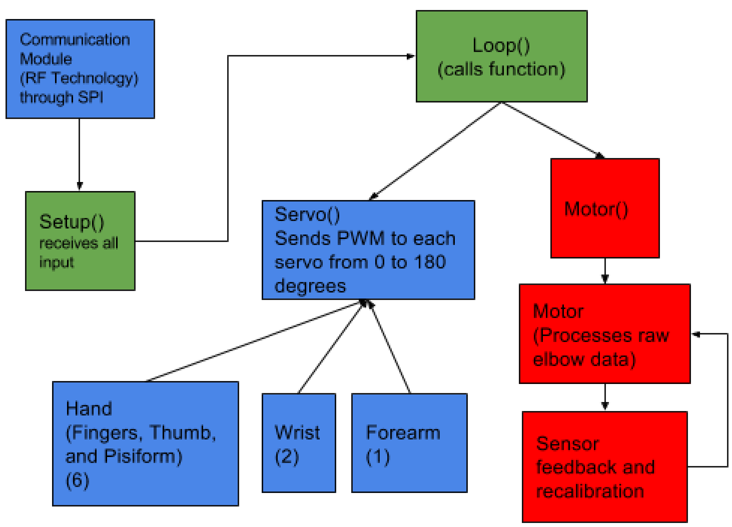


Figure 2.2.1.2.1-1: Overall Block Diagram of Arm Software

2.2.1.2.2. Software of Sleeve

As shown in Figure 2.2.1.2.2-1, the software block diagram for the sensor sleeve. Each of the 7 flex sensors will send data to the MCU. The 3 gyroscopes will also send its data to the MCU. There will be a function that processes and calibrates the data. It will then send the data through our communication module, which will be either an RF module or Wi-Fi module.

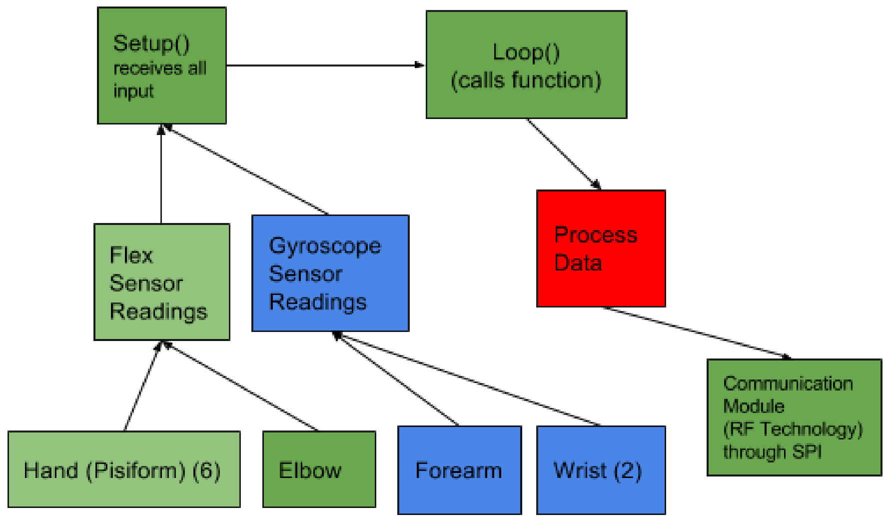


Figure 2.2.1.2.2-1: Overall Block Diagram of Sleeve Software

2.3. Requirements and Standards

Specs	***Arm***
	Shall have 6 servos for fingers and wrist.
	Shall have 2 servos for elbow.
	Shall have 5 fingers that can fully open and is resting at 0 degrees.
	Shall have 5 fingers that can fully close and at 180 degrees with the fingers closed touching the hand.
	Shall have a rotatable wrist of up to 90 degrees.
	Shall be made of 1500 grams of PLA/ABS plastic.
	Shall be mounted at the triceps with resting position of the elbow at 0 degrees.
	The elbow’s range of motion will and at 90 degrees to the bicep.
	The arm and elbow shall be accurate in mimicking the user input up to 15% error tolerance.

Table 2.3-1: Arm Specifications

Specs	***Sleeve***
	Shall have 5 flex sensors, 1 per finger.
	Shall have 1 flex sensor for the elbow.
	Each flex sensor will flex up to an angle of 180 degrees based on the finger input.
	Shall have 5 flex sensors, 1 per finger.

2.3-2: Sleeve Specifications

Specs	***Communication***
	Shall have an operating range of 900 to 930 MHz.
	Shall have an operating distance of at least 1 kilometer.
	Shall transmit data at 100 kilobits per second.
	Shall consume no more than 200 mW of power.
	Shall use a gyroscope to control the horizontal axis of the sleeve.

Table 2.3-3: Communication Specifications

Specs	***Power***
	The glove shall not consume more than 10 watts of power.
	The arm shall not consume more than 148 watts of power.

Table 2.3-4: Power Specifications

Constraints	
	Sensor inputs.
	Degrees of freedom is limited by the point in which the robotic arm is mounted.
	Simplicity of the arm, in terms of feedback for the user.

Table 2.3-5: Project Constraints

Standards:

This is a small recollection of standards that apply to our project. Due to the large number of standards per component use, we limit the number of standards included in this document.

- IEC 62133 Ed. 2.0 b:2012
    - IEC 6213 3:2012 specifies requirements and tests for the safe operation of portable sealed secondary cells and batteries (other than button) containing alkaline or other non-acid electrolyte, under intended us e and reasonably foreseeable misuse.
    - This standard is included because we are using a lithium ion battery to power the sleeve system.
- ASTM B286-07(2012)
    - Standard Specification for Copper Conductors for Use in Hookup Wire for Electronic Equipment.
    - Included since we used hookup wire to connect our individual components.
- ISO 12224-1:1997
    - Solder wire, solid and flux cored -- Specification and test methods -- Part 1: Classification and performance requirements.
    - Related to flux cored solder, which we used to permanently mount/join components.

- RS-232
  - Standard for serial communication transmission of data. The RS-232 standard is commonly used in computer serial ports.
  - The standard defines the electrical characteristics and timing of signals, the meaning of signals, and the physical size and pinout of connectors.
  - Included because we are using this standard when using our serial communication between devices.
- ISO/IEC TR 18037:2004
  - A standard specifies a series of extensions of the programming language C, specified by the international standard ISO/IEC 9899:1999. The standard includes am approach to codifying common practice and providing a single uniform syntax for basic I/O hardware (IOHW) register addressing.
  - This standard was included since the arm and sleeve systems are implemented using the C programming language.
- I2C
  - I²C uses only two bidirectional open-drain lines, Serial Data Line (SDA) and Serial Clock Line (SCL), pulled up with resistors. Typical voltages used are +5 V or +3.3 V although systems with other voltages are permitted.
  - This standard applies because of the use of it with our servo controller.
- SPI
  - SPI is a single-master communication protocol. This means that one central device initiates all the communications with the slaves. When the SPI master wishes to send data to a slave and/or request information from it, it selects slave by pulling the corresponding SS line low and it activates the clock signal at a clock frequency usable by the master and the slave. The master generates information onto MOSI line while it samples the MISO line.

2.4. Impact of Realistic Design Constraints

Economic	Due to lack of funding we cannot create the arm out of materials that are expensive such as metal, fiberglass, or carbon fiber.
	We cannot use light weight high torque servos or motors.
	We cannot use high distance communication modules.
	We cannot use high computational intensive microcontrollers.
	We cannot use a very high voltage and high amperage power supply.
	Due to cost of manufacturing we will use 3D printed material with ABD and PLA plastic.

Table 2.4-1: Economic Impacts

Environmental	Environmental standards.
	Human safety standards.

Table 2.4-2: Environmental Impacts

Manufacturability	Due to the complexity issues we have to settle at the elbow rather than going all the way to the shoulder.
	Due to the complexity of the PCB we will not be able to make more than a 4 layer board.
	Due to the complexity of a laser cut arm design, we cannot use animatronic arm based off Roy's Robotic Arm.
	Due to the complexity of manufacturing and prototyping we will use 3D printed material.
	Due to the complexity of computer vision, we will be using flex sensor and accelerometers and gyros as the input from the user.

Table 2.4-3: Manufacturing Impacts

Sustainability	Due to the material on the sleeve being cloth and the flex sensors being sewn onto the sleeve.
	The cloth material can break easily and the flex sensors can break as well.

Table 2.4-4: Manufacturing Impacts

3. Research

Research in an integral part of any project. Research allows for a better understanding of the technologies and concepts involved in making a product. Without research, many projects would fail as the people leading the project would not know how to implement the resources at hand. Research can be broken down into the five main points of this project: power, communication, processing, mechanical, and movement (in the form of motors and servos).

3.1. Power

Both the glove and arm systems will have specific power requirements. Each specific requirement will vary depending on which system is being under investigation. In both this and the design section, the glove and sleeve are interchangeable to describe the end user's accessory to control the arm.

3.1.1. Power Sources/Implementations

Power is an essential part of operating both the arm and the glove. The glove only needs a small amount of power for the operation of the sensors, control unit and communication module, while the arm while require much more power to operate its servos and motors. When dealing with the glove systems, it is known that the power supply will be using a battery, rechargeable or non-rechargeable, to power its subcomponents. When it comes to powering the arm's system components, two options must be explored.

One option for the arm's power system is to use the 120V 60Hz from a common wall socket. The other option is to follow the glove's power supply system and use batteries to power the arm. Of these two options, it must be explored further to decide whether there one be a single power supply to power the arm and gloves subsystems, or to provide a power supply for each individual subsystem. Going with the first choice would provide a more compact and organized system, while the second choice would allow each individual subsystem to have a more reliable power supply at the price of space and cost.

3.1.1.1. AC Implementation

Of the options of using a DC power source or an AC power source, a DC power source would be a straight-forward answer, as only a battery would be needed, which will be explored later. As for the AC wall socket option, some topics need to be covered.

A normal USA wall socket will output 120 volts AC at 60 hertz, which to be used by common electronics needs to be converted to DC. Normally the 120 volts AC is a bit too high and must be brought down to a working level, or otherwise known as AC to AC conversion. This is done using a transformer, which is based on the turn ratio of the transformer. Depending on the number of turns on each of the windings of the transformer, the output voltage is proportional to the input voltage times the ratio of the secondary windings to the primary windings. This is used to make the voltage from the wall socket more desirable.

Once the AC voltage is at a more desirable level, the next step is to convert the newly found signal from AC to DC. This can be done in one of a few ways. The first of which is to use a half-wave rectifier, which is a circuit that implements a single diode to allow only either the negative or positive half waves of the original signal. The half wave desired is connected to the diode while the other half wave is connected to the other end of the load. Half wave rectification usually produces more ripple than its counterparts. The next option is full-wave rectification utilizing a full bridge approach. A full bridge rectifier circuit implements 4 diodes arranged in such a way that when a positive half wave comes through only two of the diodes present will be active and pass the signal through; when the next have wave comes in the other two diodes will pass, all of which is a positive signal output. The last rectifier is also a full-wave rectifier that utilizes 2 diodes and a center tapped transformer. With a center tapped transformer, the negative terminal of the load is connected to the center of the transformer, which implies the name. More turns are required to keep the same output voltage as its full bridge counterpart. The diodes are oriented in such a way that when a positive half wave comes in only one of the diodes turns on and provides this voltage to the load; when the negative half wave comes in the other diode activates. A center tapped orientation for rectification allows for easy access of opposite polarity DC outputs.

Each of these rectifier circuits will take in and AC signal and provides another AC signal with the appropriate waves rectified. To provide the DC output desired, a capacitor is placed on the output of the rectifier circuit. Because the voltage on a capacitor cannot change instantaneously, the AC signal charges up the capacitor during its up cycles. When the AC signal begins to degrade in magnitude, the capacitor starts the discharge that stored energy to a load. During the AC signals rise and fall, the capacitor is constantly being charged and discharged, providing a relatively constant output voltage (with small ripple depending on design), which is considered DC. With more proper filtering, the ripple that is seen can be smoothed out.

When selecting a power supply for the arm, the requirements for down the line loading conditions must be kept in mind. Conditions such as voltage and current requirements for the servos, controllers, sensors, etc. Knowing a rough estimate of how much current draw all of these subsystems will require helps in the selection of the power supply. With our current configurations for the subsystems, it has been estimated that the system will draw at most 20 amps of current, with voltage requirements ranging from 3.3 volts for the MCU to 5-7 volts for the servos. Of available power supplies that will provide 20 amps throughout the system, it has been narrowed down to two that would best fit our system.

The first power supply is a Mean Well MSP-300-7.5. This power supply takes in the 120VAC 60Hz signal from a typical wall socket and transforms and rectifies that signal into a 7.5V DC signal up to 40A. It weighs about 2.1 pounds, so transportation of the power supply would not be an issue. It also works well under a varied range of temperatures, from -40°C to 70°C. The output voltage is adjustable to where we can go slightly lower or above the nominal voltage if so desired, from roughly 6.8V to 9V. The power supply has built in circuit protection for short circuiting, overloading, overvoltage, and over temperature. Figure 3.1.1.1-1 shows the relevant specifications of this power supply as it relates to the project.

MODEL		MSP-300-7.5
OUTPUT	DC VOLTAGE	7.5V
	RATED CURRENT	40A
	CURRENT RANGE	0 ~ 40A
	RATED POWER	300W
	RIPPLE & NOISE (max.) Note.2	100mVp-p
	VOLTAGE ADJ. RANGE	6.8 ~ 9V
	VOLTAGE TOLERANCE Note.3	±2.0%
	LINE REGULATION	±0.5%
	LOAD REGULATION	±1.0%

Figure 3.1.1.1-1: Specifications of MSP-300-7.5 Power Supply
(Permission Pending from Mean Well)

The second power supply under investigation for use is a Mean Well SP-240-7.5 power supply. As compared to the previous power supply, it shares many of the same physical and protection characteristics, such as circuit protection (although some vary in implementation), input requirements, and key output requirements. What differentiates the two powers supplies is firstly the SP-240-7.5 is lighter by about half a pound, which is beneficial. The operating range of temperatures also differs, with the MSP-300-7.5 we have a wider range of temperatures it may operate under. For this power supply, the maximum output current allowed is lower, which would not be beneficial to later possible expansion on the project. The rated power for this power supply is also lower (due to lowered current), so this power supply is technically weaker than the previous one. This power supply also has a slightly higher output voltage ripple, so the need for regulation for this power supply is also greater than the previous power supply. The SP-240-7.5 also has a slightly lower lower-bound for the adjustable output voltage, which can be beneficial to have since we need to drop down this voltage anyway; less power would be wasted on the regulators. Figure 3.1.1.1-2 shows the relevant specifications for the power supply.

MODEL		SP-240-7.5
OUTPUT	DC VOLTAGE	7.5V
	RATED CURRENT	32A
	CURRENT RANGE	0 ~ 32A
	RATED POWER	240W
	RIPPLE & NOISE (max.) Note.2	150mVp-p
	VOLTAGE ADJ. RANGE	6 ~ 9V
	VOLTAGE TOLERANCE Note.3	±2.0%
	LINE REGULATION	±0.5%
	LOAD REGULATION	±1.0%

Figure 3.1.1.1-2: Specifications of SP-240-7.5 Power Supply
(Permission Pending from Mean Well)

As for the glove, because of the nature of the glove, which will be worn by a user so weight and safety need to be brought into consideration, DC implementation will be used to power it. This was brought about by the general lightweight property of some batteries. Non-rechargeable batteries could be used to minimize the overall projects initial cost as well as the simplicity of just replacing the battery for use. Non-rechargeable batteries could be used also in accordance to the project’s use in its applications, such as military or medical use, where charging seems impractical. Non-rechargeable batteries can be used instantly, even after long storage, and can be carried to remote locations. Another reason for choosing a DC power source would be for the convenience of the user; using an AC power source from a wall socket would limit the user’s distance of operation. Other the other hand, an AC power source would provide virtually unlimited power and the power source would not have to be changed or charged, providing great convenience at the expense of other convenience. Finally, a DC power source would be most befitting for the glove because using the AC power source might be too much, as the glove would only require around 5V to power its circuitry, whereas the arm uses servos and motors, which require much greater power consumption. Now that the choice of power implantation has been decided for both the glove and arm systems, the choice of batteries must be explored for the glove and the arm should a DC source be used.

3.1.1.2. DC Implementation

The other option to power the systems would be to use DC power instead. Of the options of AC or DC the glove will use a DC power source, but the option to power the arm using a DC source must be explored. There are many requirements and specifications to using batteries as a power source, such as ability to recharge, capacity, memory effect, nominal voltage level, and current discharges.

3.1.1.2.1. Battery Characteristics

The ideal battery for this system has the following characteristics:

Recharging Ability: The glove is required to have a DC power source, which will come from a battery. Whether rechargeable batteries are used in the system of not does not affect the overall outcome or performance of the system because the system always requires human interaction. Having rechargeable batteries only brings convenience to the user as the batteries can be recharged after use instead of being thrown out when using disposable batteries.

Capacity: The capacity of a battery is the amount of total Amp-hours accessible when the battery is in use. This is generally normalized to 20 hour rates, meaning that a 200 Amp-hour battery will be able to supply 10 amps over the course of 20 hours. Knowing the capacity of a battery is important as it allows for how long the battery will last. Knowing the time the battery will last is imperative when knowing some of the applications this device can be used for, which directly influences the performance of the system.

Memory Effect: Memory effect only pertains to batteries that are rechargeable. This concept refers to a battery losing its maximum capacity it previously held. More specifically, the memory effect occurs when a full discharge cycle has not occurred for the battery then the battery undergoes a charging cycle. Over time, after enough improper discharge cycles being recharged, the battery will not store the original or proper amount of charge, effectively rendering the battery less efficient and effective: the battery will not work as originally intended. All the subsystems in the glove and arm require specific voltages. If these subsystems do not receive these voltages, it could lead to improper device handing or complete failure of the device.

Nominal Voltage Level: The nominal voltage refers to the normal operating voltage levels the battery provides. This is a very important specification to look for in choosing a battery. Selecting the appropriate battery is important as many subsystems require a certain voltage level to operate normally. If the battery cannot provide the voltage needed for proper operation; for example the servos will require say 5V to operate correctly, if the battery cannot supply that the servos could end up not working as intended or not at all. A battery chosen will have to maintain its specified voltage rating over any operation period.

Current Discharge: This is used to measure the charge and discharge currents of a battery. This specification is important because it determines duration and durability. The discharge current allows the battery to be used at listed capacity.

Battery discharge rate is usually measure as a C-rate, where 1C means that during normal operation, the battery will deplete in 1 hour. Another characteristic is the maximum discharge current that the battery can handle before malfunction. This must be chosen so that the battery can handle the current draw from the arm or glove.

3.1.1.2.2. Battery Types

Only batteries in consideration for the gloves power supply will be mentioned in this section. These batteries in consideration are the alkaline, lithium ion, and lithium polymer batteries.

Alkaline Batteries: The most commonly used battery is the alkaline battery. Alkaline batteries are composed of and function off a chemical reaction between zinc and manganese oxide compounds. Compared with other batteries of similar voltage ratings, alkaline batteries have a higher energy density and longer shelf. The capacity of alkaline batteries varies largely with the load association during use; as the voltage steadily declines, the total capacity of the alkaline battery depends on the application it's being used for. A typical alkaline battery has a nominal voltage of a 1.5V, so when higher voltage applications, such as the gloves operation, are required, the battery may be placed in series to get that higher voltage. The amount of current that an alkaline battery can deliver is proportional to the size of the battery. The life cycles varies based on the application it is being used in, but the alkaline battery has an average life cycle of about 6 hours. There are pros and cons for using alkaline batteries are:

PROS

- Operates well under low temperatures
- Long shelf life
- Relative cost to other choices of batteries
- Cheap in the short run
- Environmentally friendly

CONS

- Variable life cycle
- Battery can leak, causing malfunction and failure
- High internal resistance that must be overcome in circuit design
- Expensive in the long run

One possibility for use of the alkaline batteries for the glove's power supply is the Energizer E91 1.5V battery. Only the non-rechargeable battery will be considered. This battery has a nominal voltage of 1.5V, so use would have to have multiple in series to provide the required voltages in the system. This battery has a 2000mA maximum current discharge rate, which brings down the total capacity of the battery to roughly 1000mAh. Since this alkaline battery is cheap, exhausting the battery itself would not cause many issues, just a simple exchange of batteries. The size of the battery makes it idea when integrating to the system as it leaves plenty of the room for other components.

Lithium Ion Batteries: Another choice of batteries to be considered for use in the glove power circuitry are lithium ion batteries. These batteries are popularly used in today's market because they have high energy density for its weight, which is relatively much lighter than competing batteries. Lithium ion batteries are also well known for their high current ratings, making them quite an efficient selection. Having a light battery would be an idea choice for the glove as the user operating the glove has to have these electronic circuits on them, so having a lighter battery means that the glove will be lighter for operation, preventing less effort on the user side. Due to its high efficiency, lithium ion batteries tend to be more expensive than their competitors, which must be taken into account when discussing the budget for the project. Another disadvantage to using lithium ion batteries is that the batteries themselves are prone to catastrophic failure (e.g. drawing too much current could lead the battery to burst into flames, and due to the nature of the glove, this is not an ideal case), and must be circuit protected. There are pros and cons for using alkaline batteries are:

PROS

- Operates well over a large range of temperatures
- Self-discharge is low compared to competitors
- Lightweight
- Highly efficient

CONS

- More expensive than competitors
- Battery must be circuit protected

There are two possible candidates for use of the lithium ion batteries are the Energizer EA91 and GMBPower ER17505M batteries. The EA91 battery has a 1.5V nominal voltage so the battery must be used in a series configuration to obtain desired voltages. Unlike the alkaline batteries, which are made for cheap and quick use, the EA91 lithium battery has a significantly higher maximum discharge current and capacity, at 1.5A continuous discharge and 3000mAh (3 times of alkaline), respectively. The ER17505M battery has a 3.6 nominal voltage, which also would need to be used in a series configuration to obtain desired voltages, but less would be needed. This battery has a 1000mA maximum discharge current rating at 3000mAh capacity. Both of these batteries are failure protected through manufacturing. Both of these batteries are generally more expensive than the typical alkaline battery.

Lithium Ion Polymer Batteries: Lithium ion polymer batteries share many characteristics with lithium ion batteries. As compared with lithium ion batteries, the polymers tend to have the same voltage and current characteristics, as well as being lightweight when compared to its competitors. To be differentiated from its lithium ion counterparts, lithium ion polymer batteries use a gel substance to drive it rather than a liquid. They also have a higher capacity than lithium ion batteries, but suffer from being at a lower energy density due to their size being much smaller. They are also a bit more expensive than lithium ion batteries. The lithium ion polymer batteries are also much safer than its counterpart. The pros and cons for using lithium ion polymer batteries when compared to its lithium ion counterpart are:

PROS

- Lighter
- Safer
- Higher capacity

CONS

- Less energy dense
- More expensive

A choice that can be made for a lithium ion polymer battery is the GPR LIPO battery pack. This battery is in the form of a battery pack, not an AA or AAA battery. This battery has a 7.4V nominal voltage, which is advantageous as this exceeds our desired voltage, so only one would be needed and to be stepped down through regulators. This battery also has a 10.5A continuous current discharge rate with 700mAh capacity, which is lower than the other choices presented. This battery is not protected with an internal PCB protection circuit that prevents over discharging and over voltage stress through improper/irregular use, so a protection circuit will be investigated. Table 3.1.1.2.2-1 shows the specifications of this battery.

Parameter	Specification	Unit
Output Voltage	7.4	V
Maximum Output Current	10.5	A
Watt Hours	50.32	Wh
Capacity	6800	mAh
Weight	11.1 / 0.694	oz/ lbs

Table 3.1.1.2.2-1: GPR LiPo Battery Pack Specifications

One type of lithium ion battery that could be used for the sleeve power source is the LP-503562 lithium ion polymer battery. This battery is supplied by Adafruit at has a nominal voltage of 3.7V; so if this battery was selected, a series configuration would have to be used to reach a voltage suitable for the voltage regulators. The capacity of this battery is 1200mAh, which is a good capacity to have as it can supply 1.2A continuously for an hour. None of the electronics on the sleeve will be too draining or stressful and certainly will not drive more than an amp. Battery life using this battery would be expected to last at least a couple hours.

Table 3.1.1.2.2-2 summarizes the characteristics between the three battery types discussed in this section.

Battery Type	Nominal Voltage (V)	Advantage	Disadvantage
Alkaline	1.2	Cheap, has a long shelf life, and environmentally friendly	Battery can leak causing malfunction, and has higher internal resistance when compared to other batteries
Lithium Ion	3.7	Lightweight, high capacity, high energy density for its weight	More expensive, and must be circuit protection to prevent battery/system failure
Lithium Ion Polymer	3.7	Lighter than other lithium ion batteries, higher capacity, and safer than other lithium ion batteries	More expensive, less energy dense than other lithium ion based batteries, and must be circuit protected

Table 3.1.1.2.2-2: Battery Characteristics

3.1.2. Voltage Regulators

When it comes to effectively powering the system, voltage regulators are a vital part in research and design. Since both the arm and glove systems have various subsystems that have their own voltage and current requirements, the need for an efficient, effective, and accurate power supply is great. Supplying voltage too low or too high could lead to improper function or failure entirely in the system. Such an example of the vast differences each of the needs of the subsystems is that the servos for the arm will require anywhere from 5-7V and the controllers for the glove will require 3.3V for digital logic. There are several types of voltage regulators, but of the vast selection, two of them will be discussed and parts explored. Those two are linear regulators and switching regulators.

3.1.2.1. Linear Voltage Regulators

One of the effective ways to control how much voltage is supplied to a load is the linear voltage regulator. As in many cases in power supply design, the voltage requirements for components in the system may vary with the voltage of the supply that powering it. A linear voltage regulator provides a constant DC output, stepping down the input voltage, regardless of what it may be as long as it's in the regulator's specified input range. Linear voltage regulators can work by using a voltage controlled current source forcing the output voltage to be fixed. This current source does impose a limit on the output current that the regulator can provide while maintaining its voltage regulation. In order to assure stability of the system, a capacitor is connected from the output to ground. A big factor in linear voltage regulators is heat dissipation. Because of the nature of a linear regulator, normally the input and output voltages vary, which causes the difference between the two to dissipate as heat into the system. Since this can be a problem, a heat sink must be used in a lot of linear regulator applications.

There are three types of linear regulators: the standard linear regulator, the low dropout regulator, and the quasi LDO regulator. There are two crucial differences between these regulators, the drop out voltage and the ground pin current. The dropout voltage is defined as the minimum voltage difference in the input and output voltages of the regulator to maintain desired voltage regulation. The ground pin current is the current required when driving rated load currents. The higher the ground current, the more power wasted, as the current on the ground pin does not help to provide power to the system.

One benefit of using linear voltage regulators is that they can be used easily and are generally a low-cost option for implantation. Many are used in low voltage and low power systems since the differences between the input and output voltages provide small power losses and heat dissipation, so a heat sink is generally not required when in low power systems. Most of the linear regulators commercially available are easy to use since the amount of external circuitry is minimum and when external circuitry is required the design for those are not complicated. Another advantage to the linear voltage regulator is that they have very clear outputs with little to no noise and virtually no ripple in the output, as compared to switching regulators, which will be discussed in the next section. Linear voltage regulators can only step down a voltage source, which is fortunate for us since our systems do not required boosting of any voltage sources.

When used in our system, the glove requires a small amount of power as compared with the arm. The glove will be powered by one high voltage battery or a couple low voltage batteries. When these batteries are in place, linear voltage regulators can be used to step down to voltage levels used in the system, those being the sensors, control unit and communication modules, which only require low voltage and low current. When the arm is concerned, because we know that the power supply is going have to provide at least 7 volts and a good portion of the system will require less than that, a linear voltage regulator must be selected to withstand such large parameters. Since the linear regulators would have to step down the voltage to roughly 6, 5, and 3.3 volts for each of the subsystem requirements, the linear voltage regulator may need a heat sink for the low voltage conversions, as a lot of heat would be dissipated. A linear voltage regulator will still be explored for use in the arm system, but linear regulators will be used in the glove system.

3.1.2.2. Switching Voltage Regulators

Another way to control voltage distribution in an electronic system is the switching voltage regulator. A switching regulator uses the principles of pulse width modulation to move input energy to output energy, which can be controlled uses electrical switches and a controller. Because switching regulators can output the same, if not more, than linear regulators while being “on” during less time on certain applications and conditions, this makes the switching regulator an ideal choice for power regulation. Switching regulators also have the ability to step down, as well as step up or convert, voltages, which is another advantage over linear regulators. Although it has its many advantages, the linear regulator has problems when handling low load currents. Switching regulators, as the name implies, use switching technologies, and therefor can introduce noise into the system, which must be handled with through proper filtering. A couple of important characteristics of the switching regulator is the duty cycle and switching frequency, which controls the amount of energy transferred and how fast it is transferred. Typically the higher the switching frequency, the more filtering is required to prevent noise from accumulating on the power signals, but the more power that can be transferred. Switching regulators typically have several components to complement their design, such as an inductor (either on the input or output), an output capacitor, a diode, a transistor, and sometimes a transformer.

The switching regulator is a highly efficient electrical device, but this comes at a cost. A switching regulator is typically more expensive than its linear regulator counterpart. This is mainly due to more external components needed to provide line regulation (such as the inductor selected) and filtering to prevent noise. Despite this cost, switching regulators are very reliant in providing a constant output voltage. There are a variety of switching regulator types, such as the buck converter, boost converter, fly-back converter and buck-boost converter.

Buck Converter: The most commonly used of the switching regulator family is the buck converter, which is used to lower, or “buck,” the input voltage to a steady output voltage like its linear regulator counterpart. The buck converter provides the input voltage to an inductor through a transistor behaving like a switch that alternates between providing that voltage and turning off. When the transistor is “on,” the voltage difference between the input and output is forced across the output inductor, causing the current flowing through the inductor to increase. When the transistor is “off,” the voltage on the inductor will change to keep the current flowing through it constant, while the charged output capacitor will provide the voltage to the load. This process is continuously repeated, allowing for a stable, regulated output voltage.

Boost Converter: The boost converter takes the input voltage and outputs a voltage higher than that input voltage, or “boosting” it, but it must be of the same polarity. Much like the buck converter, the boost converter also uses a transistor for its switching properties. When the transistor is on, the inductor receives the input voltage, causing its current to go up. When the transistor is off, the current on the inductor because to decrease, forcing the output voltage to go positive, allowing for the diode to turn on and charge the output capacitor at a higher voltage than the input. Because boost converters ramp up the input voltage it only makes sense that due to voltage and current laws that the output current must and will be lower than the input current, which would have to be brought under consideration during design.

Fly-back Converter: The fly-back converter is one of the more unique and versatile converter topologies. The fly-back converter allows for multiple outputs, even at differing polarities. Like the other switching converters the fly-back converter uses a transistor as a switch. When the switch is on, the input voltage is seen across the transformer, which depending on the turn ratio will increase or decrease the input voltage. That then charges the output capacitor, which when the transistor is off, will discharge to the load. The orientation of the transformer primary will determine diode orientation and output polarity, which gives flexibility when designing.

Buck-boost Converter: The buck-boost converter, also known as the inverting converter, takes the input voltage and produces an output voltage of the opposite polarity. The output voltage’s magnitude may be either larger or smaller than that of the input voltage. The buck-boost converter has a very similar topology to the buck converter, while only changing the capacitor orientation and switching the spots of the diode and inductor. When the switch is on the capacitor provides the output current and output voltage. When the switch is of the inductor provides the output current.

Table 3.1.3.2-1 shows the comparisons and contrasts of linear and switching regulators.

	Linear	Switching
Function	Only steps down (buck) so input voltage must be greater than output voltage.	Step up (boost), step down (buck), inverts (buck-boost).
Efficiency	Low to medium, but actual battery life depends on load current and battery voltage over time. Efficiency is high is difference between input and output voltages is small.	High, except at very low load currents (μA), where switch-mode quiescent current (I_Q) is usually higher.
Heat Waste	High, if average load and/or input to output voltage difference are high.	Low, as components usually run cool for power levels below 10W.
Complexity	Low, usually requiring only the regulator and low-value bypass capacitors.	Medium to high, usually requiring inductor, diode, and filter caps in addition to the IC; for high power circuits, external FETs are needed.
Size	Small to medium in portable designs, but bay be larger if heat sinking is needed.	Larger than linear at low power, but smaller at power levels for which linear requires a heat sink.
Total Cost	Low.	Medium to high, largely due to external components.
Ripple/Noise	Low: no ripple, low noise, better noise rejection.	Medium to high, due to ripple at switching rate.

Table 3.1.3.2-1: Comparison of the Characteristics of Switching and Linear Regulators

(Permission Pending from DigiKey)

3.2. Processing

At the brains of this project lies a processing unit of some kind. This can be a microcontroller unit or a central processing unit. Microcontroller units are devices that have everything you need right on the chip, including the central processing unit, memory and everything in-between. Central processing units on the other hand are just that, they do all the processing, but they require other peripherals such as memory, and other inputs and outputs. Throughout this research section, there will be a discussion of the many different types of processing units. This includes a description of microcontrollers along with examples and comparisons of different units available. As well as different CPU's and platforms that could be used.

3.2.1. Background of MCU's

Microcontrollers are all around us. They are basically in all in one chip. They are composed of a central processing unit, memory units such as read only memory and random access memory, as well as flash based memory. They also have input/output pins, timers and registers. These are integrated chips that are used all around us in an embedded system. They are in microwaves, cameras, automobiles, planes. They are used to simple repetitive tasks, and are usually specialized. Due to their size, they do have constraints on memory and processing power.

Each Microcontroller executes operations that are called instructions to do a specific task. Most commonly they are used for handling input/output operations. There are a plethora of options when dealing with microcontrollers; they are usually classified by architecture, memory, programming language, speed of processor, peripherals and ease of use.

3.2.1.1. Advantages of Microcontrollers

MCU's many advantages and disadvantages. AS mentioned above, due to their size they are very easy to integrate in many applications, and are used in a variety of embedded systems. Due to the fact they are doing simple tasks, they work very fast in that regard. But on the flip side, because the tasks are very simple, microcontrollers are just that, simple. They have limitations on processing power and memory. But this is due to the fact that most MCU's are low power or in some cases ultra-low power. They can be put into a "sleep" mode in which they consume Nano amps of current. But again due to their cheap price, you can just use multiple MCU's for doing a complex task, or just use a microcomputer.

3.2.1.2. Disadvantages of Microcontrollers

Another constraint to think about is memory, due to the size of the chip; it is hard to fit a lot of memory on it. Some Microcontrollers only 16kb of RAM for code, this is not a lot, and can cause issues if you are trying to do a more complex task. Although some Microcontrollers have a new type of memory called Ferroelectric

Random Access Memory. Unlike RAM it is nonvolatile, meaning it does not need a constant power source to retain the saved data. It also doesn't have the write limitations that flash has. Flash memory can only be written 10,000 times. FRAM is faster than Flash, about as fast as RAM, and can be written and rewritten over 10 billion times. So far FRAM is only available in Texas Instruments MCU's.

3.2.1.3. Packages for Microcontrollers

Microcontrollers come in a variety of package types. A package is basically the form factor of the chip. It is the casing around the integrated circuit die. The metal connections from the die connect to a pin or pad on the package. The pin itself is made from silver, and connects to other parts of the circuit on the PCB. The package type depends on the type of components you have on the circuit board. One of the aspects to take into account is how the component attached to the board.

There are two mounting types, through whole (PTH) and surface mount (SMD or SMT). Through hole packages are just that, their pins go through from one side of the circuit board to the other side. The other side is then soldered on. These are much easier to work with as they can be prototyped on a breadboard. They are also much bigger in size compared to SMD components. Surface mount packages are only designed to go on side of the circuit board and are soldered to the surface. The pins on an SMD chip come out of the sides and depending on the chip, the pins may completely be on the bottom with no lead showing. In order to solder these chips you need special tools as the pins are usually too small to solder by hand. If you can't solder them by hand, you must use solder paste and a hot air gun or reflow oven.

Microcontrollers come in a variety of packages. The most common ones include: Dual Inline Packages and Quad Flat packages. These chips have many subsequent package types which will be discussed.

Dual Inline Package or DIP for short is the most commonly used packages. As the name suggests there are two rows of pins that are parallel that extends out of the black rectangle. To dive into more specifics, the pins are spaced out by .1 inches. This type of spacing is standard for breadboards; this makes it very easy to prototype DIP IC's. See Figure 3.2.1.3.1-1for example.

The next type of package that is used the Small-Outline Package or SOP for short. They are look like a flat DIP IC. Due to the sizing of boards there is a smaller version of the SOP package; it is called the shrink small-outline package (SSOP). They get even smaller with the Thin Small-outline package (TSOP), and Thin-shrink small-outline package (TSSOP).

Next there is the Quad Flat Package (QFP). This is the most common SMD IC for microcontrollers. They usually have anywhere from 32 to over 300 pins, with ¼ that number of pins on each side. See FIGURE1 for an example. These get even smaller with Quad-flat no-leads (QFN) which has little or no lead showing, which makes incredibly difficult to solder by hand. See FIGURE below. They get even smaller with the thin quad-flat (TQFN); very thin quad-flat package (VQFN), Micro-lead quad-flat package (MLQFP), dual no-lead (DFN), and thin dual no-lead (TDFN). Many IC's such as MPU's and microprocessors such as an IMU or Raspberry Pi respectively use a QFN package.

Finally there is the Ball Grid Array Package or (BGA). This package has no leads at all, and only has a plethora of small balls of solder on a two dimensional grid on the bottom of the package. These are reserved for advanced IC's such as Microprocessors and sensors. BGA's are almost impossible to solder by hand, they are even difficult to put on the chip by hand. In order to attach to the board, you must use a pick and place and reflow oven. They are too light and would probably fly off the board with a hot air gun.

3.2.1.4. Oscillators for Microcontrollers

In order for most microcontrollers to run at a stable frequency, such as 32.768 KHz, or 16 MHz, there needs to be an oscillator of some type. There are two types of oscillators: mechanical resonators such as crystals or ceramic resonators, or RC oscillators that use electrical phase-shift circuits involving resistors and capacitors. Figure 3.2.1.4-1 shows both an RC oscillator and a pierce oscillator.

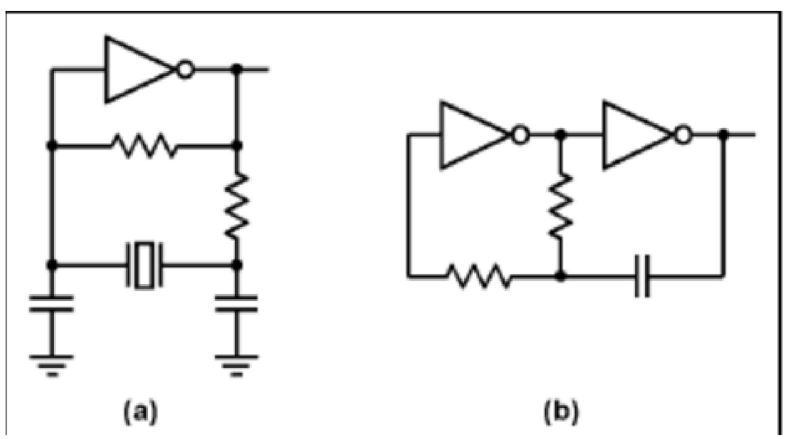


Figure 3.2.1.4-1: Schematic of Clock Sources

The biggest differences between the two clock sources are as follows. Crystal and ceramic resonators, give a very high accuracy, and low temperature coefficient. Whereas RC oscillators provide a very fast startup time and low cost, but are usually not very accurate, and are not very power efficient. Both can be disrupted by Electromagnetic interfaces, mechanical vibration and shock, as well as temperature and humidity. Table 3.2.1.4-2 shows other primary differences between clock sources that would be used in a microcontroller.

Clock Source	Accuracy	Advantages	Disadvantages
Crystal	Medium to high	Low cost	Sensitive to EMI, vibration, and humidity. Complex circuit impedance matching.
Crystal Oscillator Module	Medium to high	Insensitive to EMI and humidity. No additional components or matching issues.	High cost; high power consumption; sensitive to vibration; large packaging.
Ceramic Resonator	Medium	Lower cost	Sensitive to EMI, vibration, and humidity.
Integrated Silicon Oscillator	Low to medium	Insensitive to EMI, vibration, and humidity. Fast startup, small size, and no additional components or matching issues.	Temperature sensitivity is generally worse than crystal and ceramic resonator types; high supply current with some types.

Table 3.2.1.4-2: Clock Source Comparison

3.2.1.5. Evaluation Modules for Microcontrollers

For the scope of this project we have to create a Printed Circuit Board or PCB. This PCB will hold the Microcontroller unit. A common misconception that people have is mistaking the evaluation board for the Microcontroller itself. For instance, the Texas Instruments Launch pad series of boards are just evaluation modules for the actual chip. Basically the EVM's are there to test out and play with the MCU's peripherals, such as General Purpose Input Output, clocks, and timers. Just like the MSP430 Launchpad is the EVM for the MSP430.

The EVM also makes it easier to prototype designs. This is due to the many jumpers, and the USB emulator. This allows you to program the chip through USB, instead of directly interfacing with the chip through a debugger using JTAG. Once you remove the chip from the EVM and put it on a PCB, there has to be jumper pins included for boot loading/flashing the chip with the desired code/instructions. But for our prototyping purposes we will be using the EVMS, whatever they may be for our tests, since they are easier to work with. The methodology is to use a Launchpad/Arduino and then for all the capabilities we need use booster packs/shields. Once we have a working prototype we shrink down the EVM's onto one or two PCB's depending on size. It is possible to connect an Arduino combined with multiple shields to create a prototype of a project.

3.2.1.6. Atmel AVR’s

Let’s start with the Arduino Uno when comparing devices. This EVM using the Atmega328P. This is the one most people start out with when they are experimenting with MCU’s. They have larger ones and very small ones. Price wise, the Arduino is around 25-30 dollars. You also need to buy the USB A to USB B cable.

You get 20 IO Pins, 6 digital and 6 analog. Arduino’s are also very modular, they have many expansion options. These are other EVM’s called Shields that provide many different types of capabilities. These include: Wi-Fi, Bluetooth, GPS, servo controllers, RF control, GSM

In order to program the Arduino board you must use their IDE. But if you want to just program the chip by itself you can use an IDE made by Atmel itself.

In Table 3.2.1.6.1-1 there is a comparison between all the Arduino’s on the market. This table shows the Processer that is used, the operating and input voltage, the CPU speed, the analog inputs and outputs, the digital IO pins, the EEPROM in kilobytes, the SRAM (static random access memory) in kilobytes, and the Flash memory in kilobytes.

Processor	Operating (V)	CPU Speed (MHz)	Analog In/Out	Digital IO/PWM	EEPROM (kB)	SRAM (kB)	Flash (kB)
Intel® Curie	3.3	32	6/0	14/4	-	24	196
ATSAM3X8E	3.3	84	2/12	54/12	-	96	512
ATtiny85	3.3	8	1/0	2/3	0.5	0.5	8
ATmega168V	2.7-5.5	8	6/0	14/6	0.512	1	16
ATmega328P	2.7-5.5	8	6/0	14/6	1	2	32
ATmega32U4	3.3	8	4/0	4/9	1	2.5	32
ATmega2560	5	16	16/0	54/15	4	8	256
ATmega32U4	5	16	12/0	20/7	1	2.5	32
SAMD21 Cortex-M0+	3.3	48	1/7	4/8	-	32	256
ATmega168	3.3	8	6/0	14/6	0.512	1	16

Table 3.2.1.6.1-1: Atmel Chip Comparison

When doing specific comparisons between the chips there are many things to consider. First off, the ATMEGA328P is the most popular chip to be used on most Arduinos and most hobby boards that use microcontrollers. This is because of the support available for this chip specifically, it has a huge community support, and a majority of the Arduino users have experience with it. It has an operating voltage of 2.7 to 5.5V which makes it very easier to power with either a 3.7 V ion battery or a 9V battery. It runs at 8MHz which means it can run most applications that users would like to run. It also many analog and digital GPIO pins that can be used. It also has SPI, UART and I2C communication capabilities. This makes it a very versatile chip that’s also very cheap. It is very easy to bootload, and a lot of evaluation modules and hardware exists for it, making it very easy to implement in people’s projects.

The next chip of interest is the ATMEGA 2560. Its main evaluation module is the Arduino MEGA. This chip is commonly used on applications that require more inputs/outputs, faster speed, more memory and more communication outlets. It is basically the big brother of the ATMEGA 328P, it is the same to program just with all of the specs doubled or even quadrupled. But this comes at a price, as it is also 4 times the cost.

Both of these chips are good choices for this project, as they have a lot of community support. The issue with using more obscure chips, is mainly the lack of support. If an issue occurs, the user basically must fend for themselves. If the company doesn’t put out an example or another user hasn’t done the thing they are trying to do, then the user must figure it out themselves. This isn’t that big of an issue to an engineer that uses the chip often, but for someone who isn’t’ experienced with microcontroller units it’s a big deal. Especially if they are trying to do something new on the chip, or even bootload it.

3.2.1.7. MSP430

The MSP430 is a mixed signal microcontroller family from Texas Instruments. As mentioned MSP430 is a line of chips.

The Launchpad is about $4.30 cents and with shipping around 10 bucks from TI’s website. For this price you get the EVM and a USB cable interfacing USB B to mini USB. The MSP430G2553 is what we will be specifically speaking about in this paragraph. It has 16 IO pins, 8 analog and 7 digital. It also comes with a button and an LED. It is 16 bit RISC architecture, with integrated peripherals such as Analog to Digital Converter (ADC), Real Time Clock (RTC), multiple timers, serial modules, Ferroelectric Random Access Memory, and Op Amps. Some of the clocks can be configurable up to 16 MHz

Numbering System: There is a system used for numbering the different MSP430 devices, for instance MSP430F2618. The F stands for the type of memory, flash in this case. There is also C for masked room, FR for FRAM, G for flash value line, and L meaning Ram only. The Letter can also change based on the function, E for metering functions, G for medical instruments, W for scan meters. The 2 in this case stands for the generation, as the peripherals can change very rapidly. The 6 stands for the model within the generations. It also shows the mixture of peripherals with the pin. The 18 stands for the amount of memory on the device.

3.2.1.7.1. Comparison of Generations for MSP430

Below is a comparison of generations, the new generations cost more than the older ones, but there are tradeoffs as well. Depending on our application, we may pick an older generation, due to the price and to fully optimize the hardware. This table shows the differences between the generations, power specs, and device parameters for multiple families of MSP430’s. See Table 3.2.1.7.1-1 for differences between Microcontrollers.

The reason these parameters are mentioned are very important. The power is important if one is doing a low power application, as they don’t want to waste the battery. The memory sizes are important as well, to know how big the program can be before flashing it to the chip is something to take into consideration. The ROM and RAM also play a role in considering the chip, as you want to have a lot of this for quick operations. GPIO options, tell one how many digital and analog input and options the user has to allow the microcontroller to process. The ADC options show how many bits wide the analog to digital converter is. The more bits means a higher resolution of the signal. Finally the other integrated peripherals show the method of communication and differentiation for the chip. For instance, the DAC, the timers (including up, down, and A), the UART module, the I2C module, the multiplier’s, the comparators, the sensors that may integrated, the SPI module.

Table 3.2.1.7.1-1 shows the main differences between from the first and second generation of chips. Each has their own strength and weakness, from power optimization to amount of memory.

Device	Power Specs	Device Parameters
MSP430x1xx	0.1 µA RAM retention	Flash options: 1–60 KB
	0.7 µA real-time clock mode	ROM options: 1–16 KB
	200 µA / MIPS active	RAM options: 128 B–10 KB
	Features fast wake-up from standby mode in less than 6 µs.	GPIO options: 14, 22, 48 pins
		ADC options: Slope, 10 & 12-bit SAR
		Other integrated peripherals: 12-bit DAC, up to 2 16-bit timers, watchdog timer, brown-out reset, SVS, USART module (UART, SPI), DMA, 16×16 multiplier, Comparator_A, temperature sensor
MSP430G2xx	0.1 µA RAM retention	Flash options: 0.5–56 KB
	0.4 µA Standby mode (VLO)	RAM options: 128 B–4 KB
	0.7 µA real-time clock mode	GPIO options: 10, 16, 24, 32 pins
	220 µA / MIPS active	ADC options: Slope, 10-bit SAR
	Ultra-Fast Wake-Up From Standby Mode in <1 µs	Other integrated peripherals: Capacitive Touch I/O, up to 3 16-bit timers, watchdog timer, brown-out reset, USI module (I²C, SPI), USCI module, Comparator_A+, Temp sensor

Table 3.2.1.7.1-1: Comparison of First Two Generations

Device	Power Specs	Device Parameters
MSP430x3xx	0.1 µA RAM retention	ROM options: 2–32 KB
	0.9 µA real-time clock mode	RAM options: 512 B–1 KB
	160 µA / MIPS active	GPIO options: 14, 40 pins
	Features fast wake-up from standby mode in less than 6 µs.	ADC options: Slope, 14-bit SAR
		Other integrated peripherals: LCD controller, multiplier

Table 3.2.1.7.1-2: Power Specs of MSP430 1

MSP430x5xx	0.1 µA RAM retention	Flash options: up to 512 KB
	2.5 µA real-time clock mode	RAM options: up to 66 KB
	165 µA / MIPS active	ADC options: 10 & 12-bit SAR
	Features fast wake-up from standby mode in less than 5 µs.	GPIO options: 29, 31, 47, 48, 63, 67, 74, 87 pins
		Other integrated peripherals: High resolution PWM, 5 V I/O's, USB, backup battery switch, up to 4 16-bit timers, watchdog timer, Real-Time Clock, brown-out reset, SVS, USCI module, DMA, 32x32 multiplier, Comp B, temperature sensor
MSP430x6xx	0.1 µA RAM retention	Flash options: up to 512 KB
	2.5 µA real-time clock mode	RAM options: up to 66 KB
	165 µA / MIPS active	ADC options: 12-bit SAR
	Features fast wake-up from standby mode in less than 5 µs.	GPIO options: 74 pins
		Other integrated peripherals: USB, LCD, DAC, Comparator_B, DMA, 32x32 multiplier, power management module (BOR, SVS, SVM, LDO), watchdog timer, RTC, Temp sensor
FRAM	320 nA RAM retention	Speed options: 8 to 24 MHz
	0.35 µA real-time clock mode	FRAM options: 4 to 128 KB
	82 µA / MIPS active	RAM options: 0.5 to 2 KB
		ADC options: 10 or 12-bit SAR
		GPIO options: 17 to 83 GPIO pins
		Other possible integrated peripherals: MPU, up to 6 16-bit timers, watchdog timer, RTC, power management module (BOR, SVS, SVM, LDO), USCI module, DMA, multiplier, Comp B, temperature sensor, LCD driver, I2C and UART BSL, Extended Scan Interface,

Table 3.2.1.7.1-3: Power Specs of MSP430 2

3.2.1.7.2. Booster Packs

The Launchpad also has EVMS that expand on the capabilities of the MSP430 that stack on top of them called Booster Packs, these are the basically the same thing as shields.

3.2.1.7.3. Comparison of MSP430 vs. MSP432

The MSP432 is the newest microcontroller line from Texas Instruments. They are using the ARM Cortex-M4F CPU. It extends the 430's 20 bit address space to 32 bits. Has 4gbs for code and data. It also has faster integer and floating point calculation compared to 430. In the CHART below you can see a comparison between the MSP 430, MSP430X (which has expanded the address space to 20 bits), and the MSP 432.

	MSP430	**MSP430X**	**MSP432**
Address space	16 bits	20 bits	32 bits
Memory address space	64kB	1MB	4GB
Clock speed	25 MHz		48 MHz
Floating Point	soft		IEEE754 32 bit FPU
Typical Dhrystone 2.1 (DMIPS/MHz)	0.288 [3]		1.196
ULPBench low power score	120		167.4

Figure 3.2.1.7.4-1: Comparisons of MSP430 and MSP432
(Permission Pending From TI)

3.2.1.7.4. Software for MSP430

There are two ways to program this chip, you can use TI's own Integrated Development Environment called Code Composer Studios, and this is based on Eclipse, another popular IDE. It has a suite of tools to develop and debug embedded applications, such as the compiler, editor, build environments, debugger and profiler. This has an abstracted API called the MSP Diver Library or driverlib. It abstracts things for the user into function calls, to avoid manipulating registers. For lower level bar C, the CCS allows for full control of the chip, going down to the register level. You can view the register values in real time in debugging mode. The free version of CCS limits the code to 16kb for the MSP430.

For an easier experience TI has developed another IDE called Energia, this is an opens source program that is very similar to the Arduino IDE. You can move between the platforms very easily and most of the libraries have been ported.

Another application that can be used is the IAR embedded Workbench. It is another IDE that used in more professional applications and allows for more control of the hardware. It is much more expensive than CCS for this reason. The free version only allows for 8KB code size.

3.2.1.7.5. Power Modes for MSP430

The MSP430 also has 4 low power modes. This is a “sleep” state the MCU goes into. In these LPM states the MCU only consumes Nano-amps of current. Due to the many peripherals of the MCU, it can be awoken by “interrupts” such as button presses, or an external signal from a GPIO pin, or a timer or clock.

3.2.1.8. Advantages of Prospective Microcontrollers

These are many advantages for each microcontroller that can be used. For instance when using TI’s MCU’s the benefits are very high as one of the members has worked there, so he can ask the people who actually worked on that specific chip. Also there is TI’s E2E website, where you can ask TI employees specific questions about the project.

3.2.1.8.1. Advantages of Launchpad

Lower cost and gets you more bang for your buck. It also comes with the cable needed for use. It has a lot of support from the TI community. It is better for PWM because TI put a 16 bit timer for PWM, whereas Atmel has an 8 bi timer. It also can last significantly longer than an Atmel chip due to its ultra-low power modes. Also when using code composer, the user has much more control over the hardware, you can control the clock to any level you want, and actually find out how much power the board is consuming.

3.2.1.8.2. Advantages of Arduino

The Arduino though fairly new compared to the MSP430 has a much bigger community support. This is not to be underestimated as almost anything you want to do already have a library and someone else did the heavy lifting with the code.

3.2.1.9. Tiva C Series TMC1294

This chip is made by Texas instruments and runs a 32 bit ARM Cortex M4. It is much faster than any of the other microcontroller listed here as its frequency is 120 MHz. It is also fairly cheap, costing only $20 dollars. It has 1Mb of lash, 256KB of

SRAM, and 6KB of EEPROM. It also has integrated Ethernet ports, which is good if decide not to go wireless. Eight 32 bit timers, two 12 bit ADC's and PWM's. It also has stackable headers to put booster pack XL's.

The software consists of the cloud based Exosite quick start application. With the onboard firmware of TivaWare 2.1. In addition to this, it is compatible with code composer studios, Keil, IAR, Mentor and GCC. Although mentioned above that it has Ethernet, it does not have built in Wi-Fi so it falls flat compared to the CC 3200. On the other hand, because of the processing speed, it can handle up to 90 GPIO pins and 10 I2C ports, not to mention the 8 UART's.

3.2.1.10. CC3200 Series

The CC3200 Series chip is a great option because it has built in WIFI using the 802.11 b/g/n standard with a built in integrated radio and baseband. It includes the full internet stack on one chip. It uses the Arm cortex M4 just like the TMC1294. It doesn't run as fast, clocking out at 80 MHz. This chip has up to 256KB of ram, with 32 channel DMA, a hardware crypto engine, an 8-bit parallel camera interface. It has support for to I2C channels, one SD card, two UART's, one SPI, four general purpose timers with 16 bit Pulse with modulation, one watchdog timer, four 12 bit ADC's and 27 multiplexed GPIO pins.

On the wireless side, it completely offloads Wi-Fi and internet. It uses the industry standard BSD socket, and multiple API support. It has the capability of eight simultaneous TCP or UDP sockets, as well as two simultaneous TLS and SSL sockets. It has the capability for station, AP and Wi-Fi Connect modes. IT has built in WPA2 personal and enterprise security with an easy to use Simple Link connection manager.

In terms of power it requires 2.1 – 3.6V. In hibernate mode, it only consumes 4uA, and in Low-Power Deep Sleep Mode it requires 250uA. When receiving it uses 59mA max, and when transmitting it uses 229 mA of max power. It can use a 40 MHz Crystal with an internal oscillator or a 32.768 KHz crystal with an External RTC clock.

3.2.2. Microprocessors

A microprocessor in its simplest form is a logic chip. It contains everything needed for the CPU or central processing unit. It is considered the engine of any electronic device. It is designed to perform arithmetic and logic functions in registers. They can o adding subtracting, fetching and moving numbers. This is able to be done due to the advent of instruction sets.

The main difference between a microprocessor and microcontroller as mentioned

earlier, is that a microcontroller is seen as an all in one solution. It has the processor, RAM, memory, and I/O on one chip. A microprocessor is just that, it doesn't have RAM, ROM, or even IO built in. A microprocessor is used in general applications, as it is very versatile. This differs from a microcontroller is used for dedicated or specific operations. This is the reason why there is a micro processing unit it most personal computers, as they can do a variety of things, while a microwave or a remote would use a microcontroller.
In the following paragraphs there will be a discussion of different evaluation modules for microprocessors, such as the Raspberry PI and BeagleBone Black. The reason the evaluation module is discussed and not the chip itself. Designing a board for the microprocessor is out of scope for this project. If the group decides to use a microprocessor instead of a microcontroller, the embedded solution would be in the Arm portion and not the sensor portion.

3.2.2.1. What is a Raspberry Pi?

A Raspberry Pi unlike a microcontroller, has a microprocessor that needs an Operating system in order to run. It was developed by the Raspberry PI foundation. The PI EVM has a processor, RAM, HDMI out, a 3.5mm Jack, multiple GPIO pins, and USB ports. It is credit card sized, and it can plug into a computer monitor or TV. It can use standard keyboards, mice as well as other USB peripherals such as Wi-Fi or Bluetooth.
The raspberry pi is basically a fully operational computer. It doesn't offer internal memory, but it allows for SD cards and USB flash memory to run the operating system. While it is possible to view the OS GUI by plugging it into a TV or computer monitor, you can also access the Linux command line terminal through SSH or through an FTP server. SSH stands for Secure Socket Shell, it is a network protocol that gives administrators access to a remote computer in a secure way.

The raspberry pi requires a constant 5v and depending on the model anywhere from 1 to 2.5 amps to operate. Unlike other devices, it requires a special kind of power supply; it's not possible to just use a couple of double AA batteries. This is due to special operating system conditions, that microcontrollers don't have to deal with. When you plug a microcontroller in, it just starts executing the code/instructions that are on it, and when it is unplugged it just stops, without worrying for corruption. Again, the raspberry pi is different due to it being a full scale operating system, it needs time to boot up and there are special memory constraints that go with it.

Depending on the model, you need a Wi-Fi dongle or a direct Ethernet connection in order to access the internet. But once you are connected, there are many things the Pi excels at. These applications include, web servers, processing HTML, print servers, and even being a VPN.

In terms of sensors and General Purpose Input Output, each pi has a different amount of pins for that. The main difference between a Raspberry PI and a microcontroller is that there is an extra layer of abstraction and software in order to interface with sensors or any sort of GPIO. This in turn makes it much slower than a microcontroller, which usually has dedicated hardware and peripherals to handle this (ADC's).

3.2.2.2. Comparison of Raspberry Pi's

This was the first Raspberry Pi priced around $40 dollars USD. It came with the on board Broadcom BCM2835 chip. With an ARMv6 single core processor clocked at 700 MHz the power consumption was about 600ma at about 5V. For the GPU it used a Dual Core Video Core IV Multimedia Co-Processor. The size of this was credit card sized about 85 x 56 mm. It included about 512MB of SDRAM at 400 MHZ. With no internal memory it had a slot for a full sized SD Card. In terms of Input Output it had about 26 general purpose input output pins. 2 USB 2.0 ports. A 10/100 megabit Ethernet RJ45 Jack. Also including a Multi-Channel HD Audio over HDMI, Analog Stereo from 3.5mm Headphone Jack

In chronological order, here is how the Raspberry Pis were released. First was the raspberry Pi Model B, this started at 39.99. After this came the cheaper Raspberry pi Model A+ a cheaper, smaller board that could most of the same processing. After this came the Model B+ which included more USB and GPIO ports than the Model B. After a year came the big upgrade of the Raspberry Pi 2 model B. This included an upgrade of everything, including a better processor, more cores, faster clock speed, increased current draw, and more ram. There also was a raspberry pi zero which was a super cheap $5 dollar version of the Pi. It used the same Broadcom BCM 2835 chip running at 1 GHz. With 512 MB of ram. It used 5v and 160ma of current, which is very small. It also was very tiny, at 65mm by 30mm by 5 mm, the smallest microprocessor yet. It had the same 1080p output, but used a micro HDMI port. The main difference in the zero is that none of the GPIO pins have been populated. So if you want to use them you have to solder the pins in place. A detriment to this product is there is no Ethernet port, and there is only one USB interface, and that is microbus, which requires a USB on the go adaptor to attach anything to it.
Finally we have the Raspberry Pi 3, which just came out as we were writing this paper. This includes a boost of 300 MHz to the processor, an increase of bits from 32 to 64. The processing power is said to by 10 times faster than the original Raspberry Pi Model B. The new edition also includes the same amount of ram 1 GB but at double the frequency, from 450 MHz to 900. The biggest and most revolutionary change came from the integration of Bluetooth 4.1 and 802.11n Wi-Fi standard. The Raspberry Pi 2 and 3 also included new OS support with Windows 10. Although it is a special edition that is specific for IOT applications.

3.2.2.3. Beagle Boneblack

The Beagle Black is a microprocessor like the raspberry Pi. It is also low cost and open source, but is created by a much bigger company, Texas instruments. It also has a different chip the Sitara AM335x Arm Cortex A8. One of the biggest differences of the Beagle Bone Black and the raspberry Pi is that it ships with the software already on board. Meaning that it has 4GB of built in Flash memory. It also has support for Bunt, Android and fedora.

Like Arduino's and the MSP430 it has EVMS's that can plug directly onto the GPIO pins, these are called Capes. Speaking of GPIO, the Black has 46 pins. Diving into the specifications, the Black is about 3.4 by 2.1 inches. It has 512 MB, same as the 2nd gen Raspberry Pi's. It also has a much supported development environment, that allows for the terminal to interface directly into the browser to run Ruby, Python and INO scripts. This is done with the Cloud9IDE. It has the same 10/100 RJ45 Ethernet. Optional JTAG programming. The biggest differentiator again is the onboard 4GB eMMC flash memory that is preloaded with Debian Linux. This makes it a lot easier for the user to just plug it in and get started. It requires 5v that is powered by a DC input. It has 2 USB ports, one for host and one for client. The processor has a 1 GHz clock speed as well. It also costs around $55 dollars, which is more expensive than the other microprocessors mentioned so far.

3.2.2.4. Differentiators

As mentioned earlier, the Beagle bone has only one USB port, while the PI has 4. But the Pi can only get power from the micro-USB, while the Beagle bone has a 5vdc connection it can use. The Pi has an onboard camera interface port and LCD interface/DSI port. But the Beagle bone can add this functionally with a cape. At this point the Beagle bone black hasn't been upgraded since 2014, while the PI has continued to pump out new editions. The Beagle bone lacks in processing power, ram and software at this point. The beagle bone black can also run Android while the Raspberry Pi can't. Also, an added benefit is that it has a microcontroller that specifically handles the GPIO pins, this makes it better for robotics, sensor logging, and other things like that. The Raspberry Pi has a very good GPU, and great interface, so it is better for visual stuff, such as web server, or a media streaming device. The Pi does have a lot of more community support than the beagle bone black as well. And the Pi is cheaper than the beagle bone black at $35 dollars vs. $55. A beagle bone black is also open source, meaning you don't have to go through them in order to use the chip and design in your own product.

3.2.3. Programming Languages

With regards to software there are a plethora of choices that comes to mind. However the list gets shorter when looking at languages that can run on embedded systems such as microprocessors, and the list gets even shorter when you look at microcontrollers. Basically only C and assembly can be run on any microcontroller. This includes MSP430 and any ATMEL Chip. The assembly is the one that changes the most between the chips. The C language that is used is one step above the assembly language. The logic would stay the same, the only thing that would change is the syntax. The syntax would consist of specific register names and functions that the manufacturer has included. As mentioned earlier each manufacturer also has their own software overlay that can be used to make it easier for the user to implement a solution. For Atmel, they have the Arduino IDE overlay, which has giant community online. Texas Instruments not only has the barebones C code, they have also have driverlib C overlay, which has a plethora of functions to make the embedded software engineer to have a lot of control, but not as much as the barebones C or assembly. TI also has Energia, which is a port of Arduino's libraries.

3.3. Sensors

The sensor section is going to cover some of the sensors that is being consider to be used for this project.

3.3.1. Overview

Sensors being used for this project are considered to be a type of electrical system that is capable of providing a corresponding output to certain events or changes. Such corresponding output in this particular case would be electrical signals. There are two types of electrical signals that a sensor can provide depends on the system. The output can either be analog or digital signal depends on the system being used.

For sensor that provides analog output signal, the electrical system can be generalized as a voltage divider. The operational voltage that power the system also set a cap on the maximum output of the system, the output cannot be greater than or equal to the operational voltage. The output analog signal is provided at an intermediate point between the sensory component and the voltage dividing resistor going to the ground. The analog output signal are then process through the controller end, going through Analog to Digital Converter, otherwise known as ADC, on board the controller. This enable the controller to utilize the analog output signal in a more effective manner by the user through the manipulation of programming language used for the controller.

For sensor that provides digital output signal, the electrical system can be generalized as a black box that has corresponding mechanism within. Such mechanism would process one or more analog signals and output digital representation of the data through communication protocols like UART, SPI, or I2C. This method does not require further processing on the controller end that is receiving the data like the analog output signal does. The digital output signal would be ready to be manipulated by the user without going through a conversion process.

3.3.1.1. Arm

In order to provide feedback of the mechanical system, rotary position type of sensor would be used to measure the angular differences of certain mechanical structures. There are different types of the rotary position sensors that can be used to provide an accurate angular measurement. While certain sensors do provide better accuracy than others, the method of implementation and cost of the sensor should be considered as well.

3.3.1.2. Sleeve

In order to track the user input utilizing the sleeve, different variation of sensors such like accelerometer, gyroscopes, inertial measurement unit, and flex sensor would be considered. Focuses would be place on the output signal type, or the communication protocol, and the reliability of the sensors.

3.3.2. Accelerometer Overview

Accelerometer is a type of sensor that measures the changing force exerted on the electronic device. This could be the static and or dynamic acceleration that the body of the object is being exerting on. The principle behind the operation of this sensor can be simplified into mass held in free space by spring like structure around capacitor plates, with the movement of the mass the capacitance of the capacitor around the mass will change. By making sets of this capacitance varying structure modular and place in a perpendicular orientation, the acceleration of the mass in 3D space can then be measured. The raw sensory data obtain by this structure can then be amplified, pass through analog to digital converter, and the control logic to output in a data format that the user can interpret.

3.3.2.1. Accelerometer Solution

LIS331HH is a system on chip accelerometer solution with measurement capability of up to three axes. The onboard g-sensor is capable of measuring accelerations with output data rates from 0.5 Hz to 1 kHz. The interface is digital signal output with options of 4-wire SPI and I2C. The operation voltage of the device range from

2.16 V to 3.6 V for the onboard logic and 1.71 V to 3.7 V for the I/O. The current consumption in normal mode is typically 250 µA.

BMA180 is a system on chip accelerometer solution with measurement capability of up to three axes. The onboard g-sensor is capable of ultra-low noise and ultra-high accuracy with 14 bit ADC operation. The interface is digital signal output with options of 4-wire SPI, I2C, and interrupt pin. The operation voltage of the device range from 1.62 V to 3.6 V for the onboard logic and 1.2 V to 3.6 V for the I/O. The typical current draw in the 14 bit operation mode is up to 650 µA.

ADXL335 is a system on chip accelerometer solution with measurement capability of up to three axes. The onboard g-sensor allows the user to select the bandwidth of the output per channel using capacitors. The interface is analog signal output per channel. The operation voltage of the device range from 1.8 V to 3.6 V. The current consumption is typically 350 µA.

ADXL345 is a system on chip accelerometer solution with measurement capability of up to three axes. The onboard g-sensor is capable 13 bit ADC operation. The interface is digital signal output with options of 4-wire SPI and I2C. The operation voltage of the device range from 2 V to 3.6 V for the onboard logic and 2 V to 3.6 V for the I/O. The typical current draw with the maximum data rate is 145 µA.

3.3.2.2. Accelerometer Comparison

This section compares four different systems on chip solution for accelerometer. With focuses placed on channel/axes, range, interface, operational voltage, and current draw.

Device	Channel/ Axes	Range (g)	Interface
LIS331HH	3	±6, ±12, ±24	4-wire SPI/ I2C
BMA180	3	±1, ±1.5, ±2, ±3, ±4, ±8, ±16	4-wire SPI/ I2C
ADXL335	3	±3	3-wire Analog
ADXL345	3	±2, ±4, ±8, ±16	4-wire SPI/ I2C

Table 3.3.2.2-1: Accelerometer Comparisons 1

Device	Operational Voltage (V)	Current Draw (A)
LIS331HH	2.16 to 3.7	250 µ
BMA180	1.62 to 3.6	650 µ
ADXL335	1.8 to 3.6	350 µ
ADXL345	2 to 3.6	145 µ

Table 3.3.2.2-2: Accelerometer Comparisons 2

3.3.3. Gyroscope Background

Gyroscope is a type of sensor that measures the angular rate of change of an electronic device in 3D space. The principle behind the operation of this sensor can be simplified into modular structures like that of the accelerometer, but with an additional module that provides angular vibration to the overall system. By mixing the sensory signal of the capacitance varying structure and an angular vibration signal, any interruption to the system would affect the constant angular acceleration. With multiple capacitance varying structure placed in perpendicular orientation, the rate of change introduce by the angular vibration module allow the measurement of the angular rate of change to be taken. The raw data is then amplified, filtered, convert from analog to digital, and pass through digital filtering to be output as user perceivable data.

3.3.3.1. Gyroscope Solution

LPY503AL is a system on chip gyroscope solution with measurement capability of up to two axes. The onboard sensing unit can measure up to ±30º/s or ±120º/s with detecting rates of -3 dB bandwidth up to 140 Hz. The interface is duel axes analog output signal with amplified signal available. The operation voltage of the device range from 2.7 V to 3.6 V. The current consumption in normal mode is typically 6.8 mA.

MLX90609 is a system on chip gyroscope solution with measurement capability of one axis. The onboard sensing unit can measure up to ±300º/s with low zero rate output drift at 11 bit ADC operation. The interface is mix signal type selection, user can choose to read in the measurement in analog or in 4-wire SPI. The operation voltage of the device range from 4.75 V to 5.25 V. The current consumption in normal mode is typically 20 mA.

L3G4200D is a system on chip gyroscope solution with measurement capability of up to three axes. The onboard sensing unit allows multiple scale of degree per second and measuring rates. The interface is digital output signal with option of 4-wire SPI and I2C. The operation voltage of the device range from 2.4 V to 3.6 V for onboard logic and 1.71 V to 3.7 V for the I/O. The current consumption is typically 6.1 mA.

ITG3200 is a system on chip gyroscope solution with measurement capability of up to three axes. The onboard sensing unit allows full scale of ±2000 degree per second at 16 bit ADC operation. The interface is digital output signal I2C. The operation voltage of the device range from 2.1 V to 3.6 V. The current consumption is typically 6.5 mA.

3.3.3.2. Gyroscope Comparison

This section compares three different systems on chip solution for gyroscope. With focuses placed on channel/axes, range, interface, operational voltage, and current draw.

Device	**Channel/ Axes**	**Range (º/s)**	**Interface**
LPY503AL	2	±30, ±120	2-wire Analog
MLX90609	1	±75, ±150, ±300	1-wire Analog/ 4-wire SPI
L3G4200D	3	±250, ±500, ±2000	4-wire SPI/ I2C
ITG3200	3	±2000	I2C

Table 3.3.3.2-1: Gyroscope Comparisons 1

Device	**Operational Voltage (V)**	**Current Draw (A)**
LPY503AL	2.7 to 3.6	6.8 m
MLX90609	4.75 to 5.25	20 m
L3G4200D	2.4 to 3.6	6.1 m
ITG3200	2.1 to 3.6	6.5 m

Table 3.3.3.2-2: Gyroscope Comparisons 2

3.3.4. Magnetometer Background

Magnetometer is a type of sensor that measures the changing magnetic field around the electronic device in 3D space. The principle behind the operation of this sensor can be simplified into magneto-resistive material, material whose electrical resistance alters upon a disruption in the magnetic field, group in formation to measure the change in magnetic field of an axis. By modularizing the magneto-resistive material grid, 3 sets of them in a perpendicular orientation such like that of x-y-z-axis will allow the measurement of changing magnetic field in 3D space to be performed. The sensory data would then have to be amplified, pass through analog to digital converter, and the control logic to output a in a data format that the user can interpret.

3.3.4.1. Magnetometer Solution

HMC1053 is a system on chip magnetometer solution with measurement capability of up to three axes. The onboard magneto-resistive units can sense up to ±0.6mT.

The available interface is analog output signals per axis. The operation voltage of the device range from 1.8 V to 20 V and the current consumption in normal mode is typically 500 mA.

HMC6042 is a system on chip magnetometer solution with measurement capability of two axes. The onboard sensing unit can measure from ±1 gauss to ±2 gauss. The available interface is analog output signals per axes. The operation voltage of the device range from 2.4 V to 3.6 V and the current consumption in normal mode is typically 25 mA.

HMC5843 is a system on chip accelerometer solution with measurement capability of up to three axes. The onboard magneto-resistive units allow full range measurement of -4 gauss to +4 gauss. The interface is digital output signal with option of I2C. The operation voltage of the device range from 2.5 V to 3.3 V for analog supply and 1.6 V to 2.0 V for the digital supply. The current consumption is typically when measuring 0.9 mA.

HMC5883L is a system on chip magnetometer solution with measurement capability of up to three axes. The onboard magneto-resistive units can operate at max 160 Hz data rate at 12 bit ADC operation. The interface is digital output signal I2C. The operation voltage of the device range from 2.4 V to 3.6 V for onboard logic and 1.71 V to 3.7 V for the I/O. The current consumption is typically 100 µA.

3.3.4.2. Magnetometer Comparison

This section compares three different system on chip solutions for magnetometer. With focuses placed on channel/axes, range, interface, operational voltage, and current draw.

Device	**Channel/ Axes**	**Range (gauss)**	**Interface**
HMC1053	3	±6	Analog
HMC6042	2	±1, ±2	Analog
HMC5843	3	±4	I2C
HMC5883L	3	±8	I2C

Table 3.3.4.2-1: Manometer Comparison 1

Device	**Operational Voltage (V)**	**Current Draw (A)**
HMC1053	1.8 to 20	500 m
HMC6042	2.4 to 3.6	25 m
HMC5843	2.5 to 3.3	0.9 m
HMC5883L	2.4 to 3.7	100 µ

Table 3.3.4.2-2: Manometer Comparison 2

3.3.5. Inertial Measurement Unit Overview

Inertial measurement unit is a system on chip solution that combines sensors that is capable of measure the change of force that an object experiences, the orientation of an object, and or the magnetic field surrounding an object. Combining the sensory data of multiple axles, an inertial measurement unit, IMU, is capable of providing vector information of an object in 3D space. IMU have various applications ranging from commercial product such like smartphones to aircrafts.

3.3.5.1. Inertial Measurement Unit Solution

LSM9DS0 is a system on chip solution which integrated three different types of sensor namely the accelerometer, gyroscope, and magnetometer. This device comes in a LGA-24 package with a dimension of 4x4x1.0 mm and 24 pins. The device is equipped with the capability of measuring 3 channels of acceleration, 3 channels of angular rate, and three channels of magnetic field. For accelerometer the device have a linear acceleration full scale of ±2, ±4, ±6, ±8, and ±16 g. For magnetometer the device have a magnetic field full scale of ±2, ±4, ±8, and ±12 gauss. For gyroscope the device have an angular rate full scale of ±245, ±500, and ±2,000 degree per second. The interface is digital signal output of either SPI or I2C serial with 16 bit of data format. The analog supply voltage can range from 2.4 V to 3.6 V for logic onboard and 1.71 V to 3.7 V for the I/O. The current consumption of both the accelerometer and magnetometer is typically 350 µA and the current consumption or the gyroscope sensor is typically 6.1 mA.

LSM9DS1 is a system on chip solution which integrated three different types of sensor namely the accelerometer, gyroscope, and magnetometer. This device comes in a LGA-24L package with a dimension of 3.5x3x1.0 mm and 24 pins. The device is equipped with the capability of measuring 3 channels of acceleration, 3 channels of angular rate, and three channels of magnetic field. For accelerometer the device have a linear acceleration full scale of ±2, ±4, ±8, and ±16 g. For magnetometer the device have a magnetic field full scale of ±4, ±8, ±12, and ±16 gauss. For gyroscope the device have an angular rate full scale of ±245, ±500, and ±2,000 degree per second. The interface is digital signal output of either SPI or I2C serial with 16 bit of data format. The analog supply voltage can range from 1.9 V to 3.6 V for logic onboard and 1.71 V to 3.7 V for the I/O. The current consumption of both the accelerometer and magnetometer is typically 600 µA and the current consumption or the gyroscope sensor is typically 4.0 mA.

BNO055 is a system on chip solution which integrated three different types of sensor namely the accelerometer, gyroscope, and magnetometer. This device comes in a LGA-28 package with a dimension of 3.8x5.2x1.13 mm and 28 pins.

The device is equipped with the capability of measuring 3 channels of acceleration, 3 channels of angular rate, and three channels of magnetic field. For accelerometer the device have a linear acceleration full scale of ±2, ±4, ±8, and ±16 g. The accelerometer output signal is programmable with bandwidths of 8, 16, 31, 63, 125, 250, 500, 1,000 Hz. For magnetometer the device have a magnetic field full scale of ±1,300 µT, for x-axis and y axis, and ±2,500 µT for z-axis. For magnetic field a resolution of -0.3 µT can be measured. For gyroscope the device have an angular rate full scale of ±125, ±250, ±500, ±1,000, and ±2,000 degree per second. The gyroscope output signal is programmable with bandwidths of 523, 230, 116, 64, 47, 32, 23, and 12 Hz. The interface is digital signal output of HID-I2C, I2C, or UART. The default resolution of the accelerometer is 14 bits, gyroscope is 16 bits, and the magnetometer is 13 bits, for x axis and y axis, and 15 bit, for z axis. The analog supply voltage can range from 2.4 V to 3.6 V for logic onboard and 1.7 V to 3.6 V for the I/O. The current consumption of the device with all the sensor including the accelerometer, magnetometer, and gyroscope sensor is typically 12.3 mA.

3.3.5.2. Inertial Measurement Unit Comparison

This section compares three different system on chip solutions for inertial measurement unit. With focuses placed on channel/axes, range, resolution, operational voltage, and current draw.

Device	**Channel/ Axes**	**Range (g)**	**Resolution (bit)**
LSM9DS0	3	±2, ±4, ±6, ±8, ±16	N/A
LSM9DS1	3	±2, ±4, ±8, ±16	N/A
BNO055	3	±2, ±4, ±8, ±16	14,14,14

Table 3.3.5.2-1: IMU Comparison 1

Device	**Channel/ Axes**	**Range (º/sec)**	**Resolution (bit)**
LSM9DS0	3	±245, ±500, ±2,000	N/A
LSM9DS1	3	±245, ±500, ±2,000	N/A
BNO055	3	±125, ±250, ±500, ±1,000, ±2,000	16

Table 3.3.5.2-2: IMU Comparison 2

Device	Channel/ Axes	Range (gauss)	Resolution (x, y, z bit)
LSM9DS0	3	±2, ±4, ±8, ±12	N/A
LSM9DS1	3	±4, ±8, ±12, ±16	N/A
BNO055	3	±13 (x and y), ±25 (z)	13,13,15

Table 3.3.5.2-3: IMU Comparison 3

Device	Operation Voltage (V)	Current Draw (A)
LSM9DS0	2.4 to 3.7	6.2 m
LSM9DS1	1.9 to 3.7	4.1 m
BNO055	2.4 to 3.6	12.4 m

Table 3.3.5.2-4: IMU Comparison 4

3.3.6. Rotary Position Sensor Overview

Rotary position sensor is a type of electro-mechanical device that is capable of tracking the angular motion of the mechanical shaft and convert the change to either an analog output signal or digital output signal. There are many different type of sensors that can fit under the rotary positon sensor category. However, not all the sensors that fit under the rotary position sensor category can be used to track the mechanical system of the project due to the form factor of the sensors not fitting certain constraint of the system. Therefore, focus will be placed on infrared encoder/decoder, Hall Effect sensor, and potentiometer.

3.3.7. Infrared Encoder/Decoder Overview

Infrared encoder/decoder utilize infrared interface as optical transceiver to transmit and receive signals generated. The signal generation is done by the protocol handler, in this case the chipset. With help from an encoder disk the signal will be interrupted in certain places, when unfamiliar interrupt took place the microcontroller will be able to generalize a pattern and convert it to angular position difference.

Sector	Contact 1	Contact 2	Contact 3	Angle
0	Off	Off	Off	0º to 45º
1	Off	Off	On	45º to 90º
2	Off	On	Off	90º to 135º
3	Off	On	Off	135º to 180º
4	On	Off	Off	180º to 225º
5	On	Off	On	225º to 270º
6	On	On	Off	270º to 315º
7	On	On	On	315º to 360º

Table 3.3.7-1: Standard Binary Encoding

Sector	Contact 1	Contact 2	Contact 3	Angle
0	Off	Off	Off	0º to 45º
1	Off	Off	On	45º to 90º
2	Off	On	On	90º to 135º
3	Off	On	Off	135º to 180º
4	On	On	Off	180º to 225º
5	On	On	On	225º to 270º
6	On	Off	On	270º to 315º
7	On	Off	Off	315º to 360º

Table 3.3.-2: Gray Coding

3.3.7.1. Infrared Encoder/Decoder Solution

MCP2120 is a protocol handler that encode/decode given signal following a clock cycle given by the controller unit. The packages type that the device have to offer are 14-pin PDIP and 14-pin SOIC. The baud rate of the controller and infrared module can range from 2,400 to 312,500. The operational voltage of the device can range from 2.5 V to 5.5 V depending on the frequency selected. The maximum current consumption of device is 16 mA when the highest frequency of 20 MHz is selected.

MCP2122 is a protocol handler that encode/decode given signal following a clock cycle given by the controller unit. The packages type that the device have to offer are 8-pin PDIP and 8-pin SOIC. The baud rate of the controller and infrared module can range from 2,400 to 115,500. The operational voltage of the device can range from 1.8 V to 5.5 V depending on the frequency selected. The maximum current consumption of device is 1 mA when the frequency of 1.8432 MHz is selected.

3.3.7.2. Infrared Encoder/Decoder Comparison

This section compares two different system on chip solutions for infrared encoder/decoder. With focuses placed on baud rate, clock source, baud rate selection, operation voltage, and current draw.

Device	**Baud Rate**		**Clock Source**	**Baud Rate Selection**
	Host UART	**IR**		
MCP2120	2,400-312,500	2,400-312,500	XTAL	HW/SW
MCP2122	2,400-115,200	2,400-115,200	16XCLK	16XCLK

Table 3.3.7.2-1: Encoder/Decoder Comparison 1

Device	Operation Voltage (V)	Current Draw(A)	Frequency Selected (Hz)
MCP2120	5.5	16m	20M
MCP2122	5.5	1m	1.8432M

Table 3.3.7.2-2: Encoder/Decoder Comparison 2

3.3.8. Potentiometer Overview

Potentiometer, also known as variable resistor, allows the user to vary the voltages of a voltage divider by adjusting the mechanism associated with the component. There are slider potentiometer, thumbwheel potentiometer, and trimmer potentiometer. Slider potentiometer and thumbwheel potentiometer are meant for more frequent adjustment, whereas the trimmer potentiometer is meant for onetime adjustment for fine-tuning purposes.

Thumbwheel potentiometer will have more of the focus, due to its mechanical structure and functionality which enable rotary motion. In addition, for this project in particular, a linear taper potentiometer if favored over logarithmic potentiometer. A feedback of linear voltage differential as the angular position of the mechanical structure changes would be the goal. There are two main categories of thumbwheel, shafted and shaft-less thumbwheel potentiometer. Only shaft-less would be considered due to the mounting method to the mechanical structure. Hollowing out the axle of rotation would weaken the structure integrity, it is better to extend a shaft from the axle of rotation and put it through the component.

3.3.8.1. Potentiometer Solution

SVK3A103AEA01R00 is a shaft-less potentiometer under the linear potentiometer category. With the dimension of 14.9 mm by 11mm by 2.1 mm. The effective rotational angle is typically 333.3º with the rotational service life of at most 300,000 cycles. The maximum torque that the rotation can exert is 1mN*m. The total resistance value is 10 kΩ with the tolerance of ± 30% rated at the voltage of 5 Vdc.

RDC502 is a shaft-less potentiometer under the linear potentiometer category. With the dimension of 17.3 mm by 11mm by 2 mm. The effective rotational angle is typically 320º with the rotational service life of at most 1,000,000 cycles. The maximum torque that the rotation can exert is 2mN*m. The total resistance value is 10 kΩ with the tolerance of ± 30% rated at the voltage of 5 Vdc.

3382G-1-103G is a shaft-less potentiometer under the linear potentiometer category. With the dimension of 13.74 mm by 11mm by 2.11 mm. The effective rotational angle is typically 330º with the rotational service life of at most 1,000,000 cycles. The maximum torque that the rotation can exert is 30gf*cm. The total resistance value is 10 kΩ with the tolerance of ± 30% rated at the voltage of 5 Vdc.

3.3.8.2. Potentiometer Comparison

This section compares three different solutions for potentiometer. With focuses placed on channel/axes, range, interface, operational voltage, and current draw.

Device	**Dimension (mm)**	**Effective rotational Angle (º)**
SVK3A103AEA01R00	14.9 by 11 by 2.1 mm	333.3
RDC502	17.3 by 11 by 2	320
3382G-1-103G	13.74 by 11 by 2.11	330

Table 3.3.8.2-1: POT Comparison 1

Device	**Rotational Service Life (cycle)**	**Maximum Torque**
SVK3A103AEA01R00	300,000	1mN*m
RDC502	1,000,000	2mN.m
3382G-1-103G	1,000,000	30gf*cm

Table 3.3.8.2-2: POT Comparison 2

Device	**Resistance (Ω)**	**Tolerance (%)**	**Voltage (V)**
SVK3A103AEA01R00	10 k	±30	5
RDC502	10 k	±30	5
3382G-1-103G	10 k	±30	5

Table 3.3.8.2-3: POT Comparison 3

3.4. Motors

The motor section is going to cover the differences between motor types and some of the solutions that is being consider to be used for this project.

3.4.1. Overview

The term motor is used to describe a machine design which converts one form of energy into mechanical energy. For this project, all the dynamic of the system will be achieve through the use of electric motor by converting electrical energy into mechanical energy. Under the category of electric motor are many different types of motor classification. However, for this project the main focus will be place on brushed direct-current motor, brushed DC motor, and brushless direct-current motor, brushless DC motor. The two category of electric motor will be put in comparison to one another in terms of service life, speed and torque, ambient conditions, and control method. The comparison being made here is then going to be use to help better understand and decide which category is best suited for the mechanical system of this project.

3.4.1.1. Arm

Nonetheless, due to the complexity of the overall project in terms of the mechanical system, the designing of electric motor and the mechanism driven by the electric motor will be outside of the scope of the project. Instead, focus will be placed on controlling commercial product such like stepper motor and servomotor to manipulate the mechanical system. When considering for a stepper motor solution analysis will focus on the step size, weight, dimensions, operating voltage, current draw, and torque. As for the servomotor solution consideration, similar characteristic will be desired with additional characteristic that only applies to servomotors. The analysis will focus on modulation, weight, dimensions, operating voltage, current draw, torque, speed, motor type, rotation stability method, and gear material.

3.4.1.2. Sleeve

In addition to the dynamic aspect of the arm, providing some sort of feedback from the arm to the user would be desired. A method of feedback, known as haptic feedback, became the focus due to the similarity to the actual human feedback mechanism. The idea was to generate vibration, using vibration motor, for the user to sense, to simulate the force generated by the arm and the object that it is interacting with. In order to provide accurate haptic feedback, the vibration motor would need to be small and light weight. Therefore analysis will focus on weight, dimensions, operating voltage, current draw, vibration frequency, and vibration amplitude.

3.4.2. Background of Brushed Direct-Current Motor

The brushed DC motor section is going to cover some background information on this type of electric motor.

3.4.2.1. Anatomy

The general anatomy of a brushed DC motor consist of a case, bearing, stator magnets, motor shaft, washers, armature, commutator, brushes, and terminals. The case, bearing, motor shaft, and washers can all be considered as part of the mechanical structure of the electric motor. While the stator magnets, armature, commutator, brushes, and terminals are the electrical system that converts electric energy into mechanical energy.

The stator magnets, also known as stationary magnets, are usually made up of two or more pieces of permanent magnet poles in the shape of an arc to fit within the fixture of the electric motor. When the windings around the armature are energize with current flow to generate an opposing magnetic field to that of the stator magnets, the armature would than rotate in the direction of opposing fields. The winding of coils around the armature can be excited through the commutator, brushes, and terminals. The armature windings of small brushed DC motor are usually consist of three pole in a delta configuration to avoid moment of zero torque and short circuit condition during the operation.

In addition, for smaller brushed DC motor, usually diameter less than or equal to10 mm, there is a construction that is prefer over the conventional iron core. This particular method is known as coreless, instead of winding the wire around an armature the winding are wind in a way which the winding create a rotor structure. Even though the armature gives the motor rigid support and act as a heat sink for the winding, it also comes with additional inertia generated by the mass and the high coil inductance affects the brushes and commutator service life. While, the coreless construction generates more torque, reduce the inductance, and provide better heat dissipation.

3.4.2.2. Service Life

The service life of the brushed DC motor is limited by the brushes, which is usually made up of precious metal. Depending on the brushed material, the service life can range anywhere from a bell curve with the peak at 100 hours to a bell curve with the peak at 10,000 hours of operation. The service life can also be reduced by factors such like the current, speed, directional operation, and mechanical vibrations.

3.4.2.3. Speed and Torque

For a brushed DC motor the RPM depends on the material of the brushes, this can range from below 10,000 to above 20,000 without a gearbox. However, going above 20,000 RPM would reduce the service life due to extreme electrical and mechanical wear. Through the implementation of additional poles or a gear reduction box the torque can be increase, but the speed would decrease as the result. And as mechanical loading condition changes, more current are drawn to provide the corresponding torque until it reach the limitation of the motor design.

3.4.2.4. Special Ambient Conditions

There are numerous factors that can affect the performance of the brushed DC motor, ranging from user error to working environment of the device. When operating outside of the speed range that the motor is intended for, brushfire may result from the overheating of the brushes and the commutator. Electromagnetic noise generated by the brushes and the commutator may affect the device itself and the devices around the motor. If the environment is hazardous and the motor is not properly insulated against it, then the spark from the brushes and the commutator may result in unwanted consequences. Depends on the material that the brushes are composed of and the surrounding devices, brushes dust particle might pollute the area around the motor and certain atmospheric environment to operate properly. Lubrication is sometime use with the brushes, so the motor will only function within certain environment.

3.4.2.5. Control Method

The control of the brushed DC motor is simple, for unidirectional operation simply applies the required voltage along with the capability to output the current needed for different torque loading condition. For bidirectional operation, an H-Bridge of the corresponding voltage and current rating can be used for simple control.

3.4.3. Background of Brushless Direct-Current Motor

The brushless DC motor section is going to cover some background information on this type of electric motor.

3.4.3.1. Anatomy

The general anatomy of brushless DC motor consists of rotor, stator, bearing, and terminals. Unlike the brushed DC motor, the case of the motor is not as clear defined and the mechanical and electric system is much simpler. There exist two distant physical configurations for the brushless DC motor, with the conventional configuration being known as inrunner and the other known as out runner. The difference of the two configurations depends on how the rotor and stator is configured.

Inrunner configuration is consists of stator winding surrounding the rotor, which also act as the casing and mounting unit, along with two or more pieces of permanent magnet attached to the rotor. While, the out runner configuration is consists of stator winding surrounded by the two or more pieces of permanent magnet with overhanging rotor. In either configuration, the winding is stator and also serve as mounting point for the motor.

3.4.3.2. Service life

The service life of the brushless DC motor is limited by the ball bearing that the rotor rest on. Compared to the brushed DC motor, the service life of the ball bearing can be better estimated with accuracy. And typically the service life of the ball bearing surpasses 10,000 hours of operation.

3.4.3.3. Speed and Torque

For brushless DC motor of similar anatomy structure setup in terms of the magnets and armature, it is capable of reaching a RPM of greater magnitude compared to that of brushed DC motor. The torque can be increase using similar method used to increase the torque of a brushed DC motor.

3.4.3.4. Special Ambient Conditions

Much unlike the brushed DC motor, brushless DC motor can function in a lot more environment that the other cannot. This is the result of less mechanical dependency in terms of converting electric energy to mechanical energy, the brushes and commutator.

3.4.3.5. Control Method

The control of brushless DC motor is more difficult compared to that of brushed DC motor, additional electronic device would be need for unidirectional or bidirectional operation. Electronic device known as the electronic speed controller, ESC, is used to control the rotation of the motor.

3.4.4. Stepper Motor

The stepper motor section is going to cover some background information on this type of electric motor.

3.4.4.1. Anatomy

Stepper motor is a type of brushless DC motor in the inrunner configuration with little “teeth” machined onto the permanent magnet that resides on the rotor. This type of motor does not require feedback, as long as is not over loaded mechanically, and due to the nature of the operation the motor will only rotate the set number of step instructed by the controller.

3.4.4.2. Speed and Torque

The speed of the stepper motor can go as fast as the current can be switch on and off the h-bridges through the steps. Of course, the speed also depends on the load condition of the system. Whereas the torque output of the stepper motor is higher by default without the need of reduction gears, this has a lot to do with the anatomy of the stepper motor.

3.4.4.3. Control Method

This type of motor can be control through energizing different set of coil, phase, and the heavily “teethed” rotor would rotates in small step of fixed angle in the corresponding direction. In addition, controlling this type of electric motor is not as demanding as a normal brushless DC motor. For each set of coil there will be a corresponding H-Bridge, which control the current flow, and by activating the H-Bridges in sequences the rotor of the stepper motor will rotate in small step of fixed angle with precision.

NEMA	Weight (g)	Steps/Rev	Dimensions (mm)
8	60	200	20 by 20 by 30
11	110	200	28 by 28 by 32
14	130	200	35 by 35 by 26
14	140	200	35 by 35 by 28
14	180	200	35 by 35 by 36

Table 3.4.4.3-1: Stepper Motor Comparison 1

NEMA	Voltage (V)	Current (A)	Torque (g-cm)
8	3.9	0.6	180
11	3.8	0.67	600
14	7.4	0.28	650
14	10	0.5	1000
14	2.7	1	1400

Table 3.4.4.3-2: Stepper Motor Comparison 2

3.4.5. Servomotor

The servomotor section is going to cover some background information on this type of dynamic solution.

3.4.5.1. Anatomy

The servomechanism is made up of an electric motor, set of reduction gears, drive shaft, drive shaft structure support, feedback sensor, feedback sensor structure support, and controller.

The electric motor used for the low-end servo are usually brushed DC motor, iron core motor are commonly found in servo of larger form factor where coreless motor are used for servo of smaller dimension. While brushless DC motor are often used in high-end servo. However, due to the complexity of the control method, brushless DC motor servo requires more electronic component which in terms raise the cost of the brushless servo. Granted, servo that utilizes brushless DC motor does have longer service life compared to their counterpart, but costs are unbearable for the project budget.

The set of reduction gears help reduce the speed of the motor and increase the torque output of the motor to the drive shaft. The reduction gears used for servo can be categorized into two types, non-metal gears and metal gears. For non-metal gears the material commonly used by the industry are nylon and Karbonite, whereas for metal gears the material commonly used by the industry are brass alloy, copper alloy, aluminum alloy, and titanium. Both types have their advantages and disadvantages, depends on the application of the user. Generally speaking for high torque application, where heavy mechanical load is placed on the drive shaft, a condition call “stripping” would occur. This is when the tooth of the reduction gears momentarily disengage and grind against one another, over time the tooth of the gear would grind away. Non-metal gears are unable to handle high torque as well as the metal gears, but the metal gears wear out faster than their counterpart for the most part. On the other hand, non-metal gears weights less than their metal counterpart. However, there is one type of metal material that can be considered as the exception when it comes to the wearing of metal gears and in terms of weight. That is gears machine out of titanium, which is commonly found in high-end servos. One setback that might discourage the user is the cost of this kind of servo.

The feedback sensor that is commonly used for servo is potentiometer, in configuration of voltage divider to provide an analog input to the controller. Other feedback sensors used with more sophisticated controller includes but not limited to rotary encoder and Hall Effect sensor. These are usually used for high-end servo to provide a more precise feedback.

The controller board consists of voltage converter module, error amplifier module, and motor control module. The voltage converter module takes the input signal from the microcontroller and output a voltage. The output voltage from voltage converter module then becomes one of the two inputs for the error amplifier module, while the other input of error amplifier module comes from analog feedback sensor. The error amplifier module would then output a control input for the motor control module which provide a modulation output to the electric motor.

3.4.5.2. Speed and Torque

The speed of the servomotor depends on the supply voltage, if the loading of the system can still be overcome by the torque. The torque of the servomotor is achieved through the usage of a set of reduction gears.

3.4.5.3. Control Method

Servo motors are control by using pulse-width modulation, PWM, generated from a microcontroller. By manipulating the width of the pulses sent to the servo, this will inform the servo what angular position the drive shaft need to turn to or hold at. There are two rotational movement methods for servo motor, which is continuous rotation and none-continuous rotation servo motor control. The pulse width used to control the two movement methods are the same, the only differences being the response from the servo motor.

For continuous rotation servo motor, the pulse width of 1,500 µs is set to be stop. This means when a pulse width of 1,500 µs is send to the servo motor through PWM, the servo motor would not move at all. Any pulse width to the north or the south of 1,500 µs would rotate the servo motor in clock-wise or counter clock-wise direction respectively. While the pulse width 2,000 µs and 1,000 µs is the maximum pulse and minimum pulse width that can control the servo motor. It is important to know as the magnitude of the differences of the pulse width, the rotational speed would increase. This meant that at 1,000 µs the servo would be rotating in the counter clock-wise direction at the maximum rotational speed. On the other hand, if the pulse width was at 2,000 µs, then the servo would be rotating in the clock-wise direction at the maximum rotational speed.

For none-continuous rotation servo motor, the pulse width of 1,500 µs will set the servo arm position to 90º. As the pulse width decrease to 1,000 µs, the servo arm would swing in the counter clock-wise direction till it hit the 180º mark. Whereas the pulse width increase to 2,000 µs, the servo arm would swing in the clock-wise direction till it hit the 0º mark.

One common solution to control a servo motor is utilizing the pins of a microcontroller that is capable of generating PWM signals. Though this solution is simple enough, it would only work if the number of servos to be control is less than the number of PWM enable pins that the microcontroller have to offer. Instead of adding additional microcontroller, a PWM driver would be prefer to control multiple servo motors while freeing up digital I/O pins that is capable of generating PWM.

To realize this in the project for servo motor control, PWM driver PCA9685 would be used to generate up to 16 PWM at a 12 bit resolution though digital interface of I2C bus. Even though this particular chip is sold as a solution to LED controller, the chip is capable to generate PWM signal to control servo motors.

3.4.5.4. Modulation

The motor control method for the servos divides them into two category, this distinction is based on the modulation method of the motor control. One method of modulation is known as analog, while the other is known as digital. Imagine a window that is observing the voltage sent over to the motor to control it, the differences between analog and digital is the frequency of which the voltage are being sent. For analog modulation, the pulse being sent to control the motor is standardized to 50 cycles a second.

3.4.5.5. Micro

The micro-class servo motor is capable of providing sufficient torque its weight and dimensions. This class of servo would be useful for mechanical mechanism that does not require a high amount of torque along with a size constraint.

Futaba S3153, Hitec HS-46HB, Hextronik HXT900, Power HD D65HB, and TowerPro SG90 are being compared here.

Brand	**Weight (g)**	**Speed (sec/60º)**	**Dimensions (mm)**
Futaba	9.6	0.11	22.1 x 10.9 x 20.1
Hitec	7.9	0.14	23.4 x 9.7 x 22.4
Hextronik	9.1	0.12	21 x 12 x 22
Power HD	6.5	0.07	20.8 x 11 x 20
TowerPro	9.0	0.12	23 x 12.2 x 29

Table 3.4.5.5-1: Micro-Servomotor Comparison 1

Brand	**Modulation**	**Voltage (V)**	**Torque (kg-cm)**
Futaba	Digital	4.8	1.37
Hitec	Analog	4.8	1.01
Hextronik	Analog	4.8	1.60
Power HD	Digital	6.0	1.50
TowerPro	Analog	4.8	1.80

Table 3.4.5.5-2: Micro-Servomotor Comparison 2

Brand	Motor Type	Gear Type	Rotation Stability method
Futaba	3-pole	Plastic	Dual Bearings
Hitec	3-pole	Plastic	Single Bearing
Hextronik	Coreless	Plastic	Bushing
Power HD	Brushed	Plastic	Bushing
TowerPro	3-pole	Plastic	Bushing

Table 3.4.5.5-3: Micro-Servomotor Comparison 3

3.4.5.6. Standard

The standard-class servo motor is capable of providing more torque with greater weight and larger dimensions compared to the micro-class servo motor. This class of servo would be useful for mechanical mechanism that require a higher amount of torque and is more lenient when it comes to size.

Futaba S9404, Hitec HS-525MG, Hextronik HXT12K, Power HD DC-1217MG, and TowerPro MG996R are being compared here.

Brand	Weight (g)	Speed (sec/60º)	Dimensions (mm)
Futaba	55	0.11	39.1 x 20.1 37.3
Hitec	51	0.13	39.6 x 19.6 x 35.8
Hextronik	47.9	0.13	39.6 x 20.1 x 38.1
Power HD	62	0.11	40.3 x 20.2 x 37.2
TowerPro	55	0.15	40.7 x 19.7 x 42.9

Table 3.4.5.6-1: Standard Servomotor Comparison 1

Brand	Modulation	Voltage (V)	Torque (kg-cm)
Futaba	Analog	4.8	5.7
Hitec	Analog	6.0	4.10
Hextronik	Digital	6.0	14.98
Power HD	Digital	6.0	15.80
TowerPro	Digital	6.0	11

Table 3.4.5.6-2: Standard Servomotor Comparison 2

Brand	Motor Type	Gear Type	Rotation Stability method
Futaba	coreless	Metal	Dual Bearing
Hitec	5-pole	Metal	Single Bearing
Hextronik	N/A	Metal	Single Bearing
Power HD	Coreless	Metal	Dual Bearings
TowerPro	3-pole	Metal	Dual Bearings

Table 3.4.5.6-3: Standard Servomotor Comparison 3

3.4.5.7. Large

The large-class servo motor is capable of providing a large amount of torque at the cost of weight and dimensions. This class of servo would be useful for mechanical mechanism that does require a high amount of torque with little to none size constraint.

Futaba S3306MG, Hitec HS-805MG, and TowerPro 9085MG are being compared here. Hextronik and Power HD does not have servo in this class.

Brand	**Weight (g)**	**Speed (sec/60º)**	**Dimensions (mm)**
Futaba	130	0.16	66 x 30 x 57.1
Hitec	197	0.18	66 x 30 x 57.7
Hextronik	N/A	N/A	N/A
Power HD	N/A	N/A	N/A
TowerPro	180	0.16	67.8 x 30.2 x 55.9

3.4.5.7-1: Large Servomotor Comparison 1

Brand	**Modulation**	**Voltage (V)**	**Torque (kg-cm)**
Futaba	Analog	6	23.98
Hitec	Analog	6	24.7
Hextronik	N/A	N/A	N/A
Power HD	N/A	N/A	N/A
TowerPro	Digital	6.0	25

3.4.5.7-2: Large Servomotor Comparison 2

Brand	**Motor Type**	**Gear Type**	**Rotation Stability method**
Futaba	3-pole	Metal	Duel Bearings
Hitec	3-pole	Metal	Duel Bearings
Hextronik	N/A	N/A	N/A
Power HD	N/A	N/A	N/A
TowerPro	N/A	Metal	N/A

3.4.5.7-3: Large Servomotor Comparison 3

3.4.6. Vibration Motor

The vibration motor section is going to cover some background information on this type of electric motor.

3.4.6.1. Anatomy

There is both brushed and brushless vibration motor on the market, both with different variation. One variation has a visible motor shaft with an eccentric mass counter weight attach to it, while the other is without a visible motor shaft and fitted in a coin form factor. However, the brushless vibration motor cannot be used to provide sharp haptic feedback due to electrical commutation. Brushless vibration motor is incapable to perform voltage over-drive and reverse-drive signals, which are both essential to a distinct haptic feedback. This help limit the option to brushed vibration motor.

3.4.6.2. Frequency and Amplitude

The frequency of the vibration motor is how often the motor would provide a swing, or feedback, to the user. While, the amplitude is the magnitude of the swing the user is experiencing. For the application being focus on here, a rapid and noticeable feedback would be favorite over casual and weak feedback.

3.4.6.3. Control Method

The control of the brushed vibration motor is simple, for unidirectional operation simply applies the required voltage along with the capability to output the current needed for different torque loading condition. And in this case in particular, unidirectional operation is what is needed in order to achieve the vibration.

Model	Weight (g)	Dimensions (mm)
306-109	2.7	6 by 16.7
308-102	3	8 by 16.8
C08-001	0.95	8 by 3.25
C10-000	1.6	10 by 3.1
C10-100	2	10 by 3.65

Table 3.4.6.3-1: Vibration Motor Comparison 1

Model	Voltage (V)	Current (A)	Frequency (Hz)	Amplitude (G)
306-109	3	0.075	213.333±42.5	3.65
308-102	4.5	0.145	316.667±63.333	5.5
C08-001	1.8	0.053	235±5	1.4
C10-000	2	0.075	205±10	1.7
C10-100	2	0.069	175±5	1.5

Table 3.4.6.3-2: Vibration Motor Comparison 2

3.4.7. Summary of Motors

Utilizing brushless DC motor in a project would yield greater benefit in the long run versus the alternative option of brushed DC motor. The service life of the brushless DC motor is much longer, by a significant magnitude even. However, this comes at a price of the control system that is required to command the brushless DC motor. The control systems would in terms increase the total cost of the overall system. If the project was given sufficient funding and a long time frame, then perhaps the selection of brushless DC motor related solution would be a solid decision rather than a considerable option that is outside of the budget. Therefore, only brushed DC motor servo motor is being considered for the dynamic system of the project. A servo motor of larger form factor would be considered if more torque is required, rather than the alternative option of stepper motor.

Same can be said for the vibration motor aim to provide haptic feedback to the user. However, in this case in particular brushless option was thrown out due to the back EMF it utilizes to reach optical operational phase. The back EMF would interfere with the haptic feedback generated for the user and disrupt the quality of the feedback.

3.5. Communications

The topic of communication is very important for this project, because without having a successful communication link between the sleeve and the arm there would be no way for the arm to mimic the user controlled sleeve. The only communication requirement in this project is to allow a transfer of data between the sleeve and the arm wirelessly, but having increased security, long range, and low power consumption are all important factors when it comes to choosing the correct standard. However these wireless devices have to operate in the 900-930 MHz, 2.4 GHz, or 5 GHz range due to those being the unregulated ISM (industrial, scientific, medical) radio band stated by the Federal Communications Commission (FCC).

3.5.1. Wi-Fi

The first wireless standard that needed to be researched is the all-important IEEE 802.11 standard (Wi-Fi) which operates in 2.4 or 5 GHz range. This standard was released in 1997 with the intent of replacing the older IEEE 802.3 standard (Ethernet). Due to its objective of replacing Ethernet, Wi-Fi has the added advantage that it was built from the ground up to get devices onto the internet and because of this original intent, Wi-Fi is very closely integrated with the TCP/IP stack thus allowing for a much easier time in getting devices connected to the internet. The main governing standard of the internet is the internet protocol (IP), so having a communication standard so closely related to IP is a very nice boon in favor of Wi-Fi.

Another benefit to using Wi-Fi is the added security that has been developed due to the popularity of Wi-Fi. Utilizing a security protocol like WPA2-PSK would allow for a secure connection where no outside force can manipulate, which no other wireless standard really has.

One issue that plagues Wi-Fi and thus all of its subsets is the fact that there is a lot of interference within the 2.4 GHz band due to the competition of devices like phones and microwaves that also operate at that band range. Another issue is that Wi-Fi mainly works off the star and mesh network scheme, which isn't necessary for this project. The 802.11 standard has been continually updated throughout the years, creating many different subsets that were created in order to solve different types of issues such as improving the data rate or increasing the connection strength between different devices. The subsets that best fit the needs for this project would be between 802.11g, 802.11n, and the newer 802.11ac.

3.5.1.1. Which Subset to Choose?

When talking about Wi-Fi it is important to point out which subset one is referring to due to how vast the 802.11 standard is. Like previously stated in section 3.5.1., the best subsets to look at for this particular project would be 802.11g, 802.11n, and 802.11ac. Each of these three different variations offers different pros and cons that will be looked at within this section. Since all three of these subsets are all based off the same original standard, 802.11, they all have the same security protocols and roughly the same power consumption. This leaves only two real criteria's to look at, that being throughput and optimal range.

Let's first start off with 802.11g. Between the three variations chosen, 802.11g is the oldest of the bunch and thus lacks some of higher data rates that the 802.11n and 802.11ac can offer, however 802.11g has one important positive that the others do not possess and that is the fact that 802.11g is backwards compatible with 802.11b an even older standard. This is important if the communication module that one is looking for needs to be able to "talk" to another module that is still operating with 802.11b. However that is virtually the only main advantage that 802.11g provides compared to the other two subsets. 802.11g has a much slower data rate at a measly 54Mbps, an average outdoor range of 460ft and an average indoor range of 125ft. One more disadvantage that 802.11g has is the fact that it is stuck utilizing the 2.4 GHz band range with no other possible alternatives, this band range isn't necessarily bad however it is saturated with a lot of competition that can interfere with the signal thus lowering the overall throughput/range and also helps inject noise into the transmitted signal which is something that should be avoided.

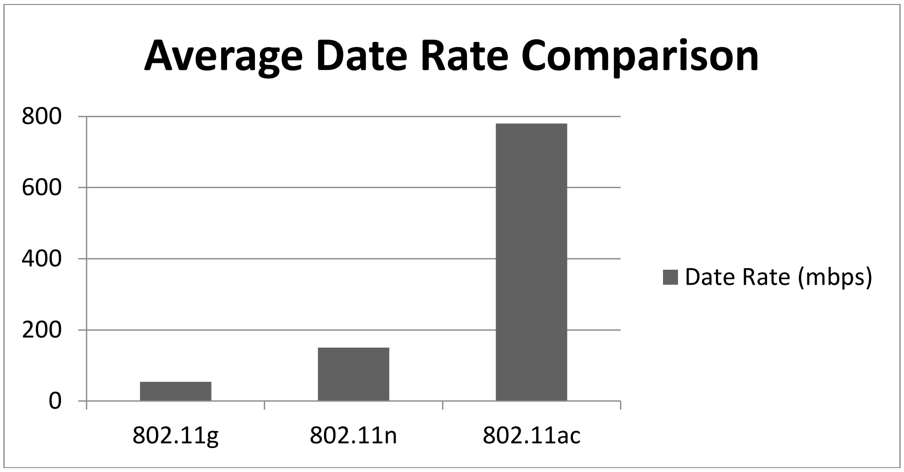


Figure 3.5.1.1-1 Average Data Rates

The second subset is the current standard for Wi-Fi devices, that being 802.11n. This one provides the best of both worlds when it comes to performance and range. It vastly out performs 802.11g in both terms of range and data rate; 802.11n can operate as far out as 820ft in the outdoors, up to 230ft indoors, and can achieve a rough average of 130Mbps per antenna (up to a max of 3 antennas). Just like 802.11g, 802.11n has a unique advantage all to itself which is that 802.11n can operate at either the 2.4 GHz band or the 5 GHz band which neither of the other two subsets can claim. This is very important because it would allow being able to change between one band or to the other without having to change the communication module, which helps save money and allows the user to choose which band that is best suited for the current environment.

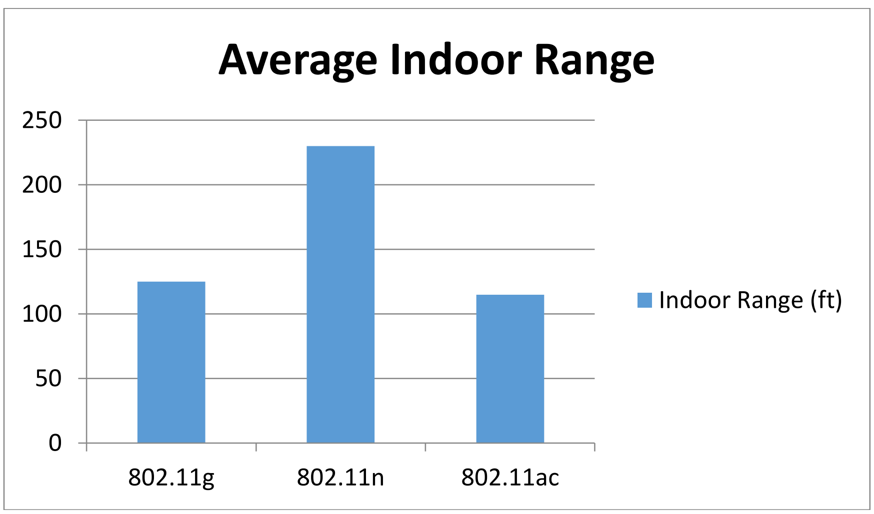


Figure 3.5.1.1-2 Average Indoor Range

The third and final subset is the 802.11ac standard, which is the newest in the bunch and is still being developed. 802.11ac is also known as the "gigabit Wi-Fi" due to its most important feature of being able to reach 1.3Gbps in data throughput, however in order to do this 802.11ac is restricted to using only 5 GHz thus losing the choice that was provided by 802.11n. 802.11ac is also able to hit about 115ft indoors and 410ft outdoors.

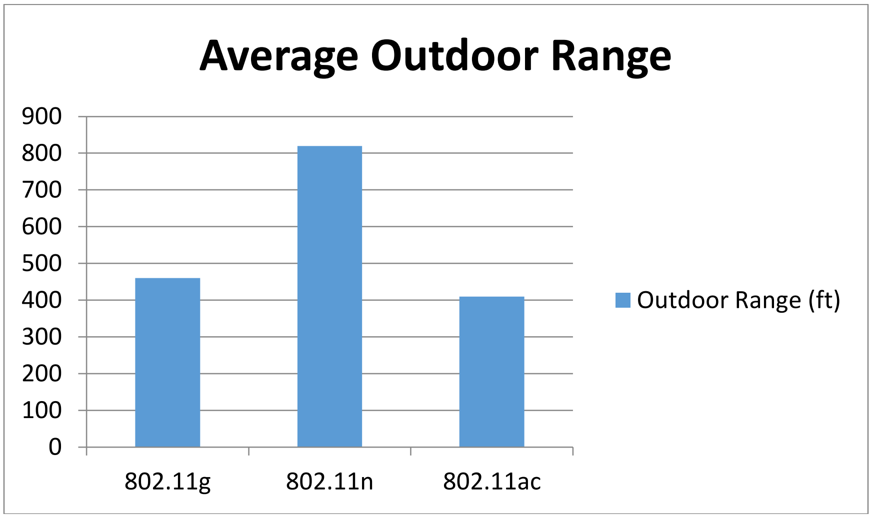


Table 3.5.1.1-3 Average Outdoor Range

After comparing the three main subsets together by looking at any significant benefits that they may provide, their data output, and their maximum range (both indoor and outdoor) it seems that the best subset to choose for this project would be 802.11n. The main benefit of 802.11ac is the fact that it can reach very high throughput, however this comes with the cost of being restricted to 5 GHz band which has worse penetration through walls and a lower maximum range; this trade-off isn't worth it because the very high data rate would just go to waste. The main benefit to 802.11g is that it is backwards compatible with 802.11b, however since this project doesn't require being compatible with that older standard, and the fact that it has a much lower range than 802.11n, it is also an inferior choice. This leaves 802.11n being the best Wi-Fi standard to use for this project if Wi-Fi is chosen.

3.5.1.2. Which bandwidth to use?

Since 802.11n was the chosen subset for the Wi-Fi standard, it is important to note which of the two bandwidths should be the main focus for this project. Like mentioned in section 3.5.1.1, 802.11n can utilize both the 2.4 and 5 GHz band, thus it is important to note which one should be the main focus.

Utilizing 2.4 GHz band would allow for double the range than a 5 GHz band (see Table 3.5.1.1-2 and 3.5.1.1-3) this is very important because one of the main scopes of this project is to have the "Helping Hand" being able to diffuse live bombs, and it would be very advantages to have a higher range to help prevent any casualties. The fact that 2.4 GHz band has nearly double the penetration power of the 5 GHz band will allow for a stronger connection between the sleeve and the arm when dealing with indoor environments. Due to 5 GHz band requiring more power in order to achieve the higher frequency and much higher throughput, it also increases the overall power consumption of the device which is a negative factor when trying to limit the amount of energy being used for such a device. The 2.4 GHz band only allows for 11 channels of communication between devices, compared to 5 GHz band that has over 4 times the amount of channels at 48; this allows for those communicating with the 5 GHz band to have less competition and thus less chance for noise causing interference. This is further amplified by the fact that there are more devices utilizing the 2.4 GHz band that clutter these 11 channels (microwaves, phones, Bluetooth). It is important to note that with over 4 times of channels, the 5 GHz band can output at 1.3 Gbps which is over double of the maximum output of 802.11n which is at 430Mbps (look at Table 3.5.1.1-3 for average rates).

After comparing between the two bandwidths, it seems to be that the 2.4 GHz band would be best suited for this project. The advantages of the 5 GHz band are important to notice, having a much higher throughput and much less interference are both great points, but despite those great points, the advantage of having a much higher range with 2.4 GHz, lower power consumption, and better connection strength through walls ultimately matter more. For these reasons, 802.11n at 2.4 GHz is the best combination for the Wi-Fi standard for this project.

3.5.1.3. Wi-Fi Module

The current Wi-Fi module that best fits the needs of this project and that can work with the Arduino would be the ESP8266. This module allows the Arduino to access the 2.4 GHz band and connect to other devices by using either 802.11g or 802.11n, but for this project the chosen subset to use will be the 802.11n standard. Any and all important information for this module will be displayed in Table 3.5.1.3-1. The ESP8266 also comes in at a reasonable cost of $6.95 from SparkFun.com.

Categories	Items	Values
Wi-Fi Parameters	Wi-Fi Protocols	802.11 b/g/n
	Frequency Range	2.4 - 2.5 GHz
Hardware Parameters	Peripheral Bus	UART/SDIO/SPI/I2C/I2S/IR Remote Control
	Operating Voltage	3.0V - 3.6V
	Average Current	80mA
	Package Size	5x5mm
Software Parameters	Security	WPA/WPA2
	Encryption	WEP/TKIP/AES
	Network Protocols	IPv4, TCP/UDP/HTTP/FTP

Table 3.5.1.3-1 ESP8266 Data sheet

3.5.2. Bluetooth

Bluetooth is a very popular standard that allows for two devices to begin communicating between each other very fast and easy. It first originated as the IEEE 802.15.1 standard which was established in 2002 in order to have an easy time establishing a connection between devices in short range of each other, thus creating a personal area network (PAN). Since Bluetooth was created with the idea of being a PAN communication standard, the range of Bluetooth 2.0 is very small at roughly 30ft, and it also has a low data rate at about 3Mbps. Bluetooth operates at the 2.4 GHz range just like Wi-Fi does, thus it also suffers from the lack of channels, the high cluttering of those channels, and all the noise that is created by interference. Another issue that Bluetooth faces is the lack of real security. Bluetooth's security ideology is to set your device into "non-discoverable" mode so other Bluetooth devices cannot pick it up, Bluetooth also uses a system like Window's User Access Control which locks Bluetooth applications from being able to do anything unless the user grants permission to those applications, and finally there is a 128bit password one can set in order to secure their device. Bluetooth does have the upsides of being cheap and having very low power consumption which is a very important for this project. Bluetooth's network topology is nothing more than peer2peer, which is much different from Wi-Fi's star and mesh topologies. Peer2peer is a much simpler network to set up and best matches the idea for this project since there will only be two objects that are interacting with each other in the network. Bluetooth is not an IP based communication standard, unlike Wi-Fi, thus making it a bit more difficult to get the system onto the internet, however since that is more on the lines of being a non-functional requirement, that isn't really much of an issue.

Bluetooth standard comes in four main version updates, Bluetooth v1-v4. With each update to the standard, Bluetooth has been able to increase its maximum range and overall data throughput for all of its devices. During the time of Bluetooth v1.0, the standard was suffering from many different problems such as connection issues and having to have a mandatory hardware device address known as

BD_ADDR when dealing with transmission in the connecting process. After Bluetooth v1.0 was updated to v1.2, there was an overall increase to the connection speed, topping off at 721 kilobits per second. There was also introduction of having a faster connection/discovery time and allowed hopping between different networks channels allowing the device to find the least cluttered. With the introduction of Bluetooth v2.0, there was another increase of data speeds to a maximum of 3 megabits per second. There was an introduction of lower power consumption and a reduction of complexity when dealing with multiple channels. With Bluetooth v3 and v4, there has been introduction to new capabilities such as another increase of maximum speed to 24 megabits per second, and a further reduction of power usage. This data can be further summarized in table 3.5.2-1.

Class	Max permitted power		Typical Range (m)	Data Rate (Mbit/s)
	(mW)	(dBM)		
V1.0	100	20	100	1
V2.0	2.5	4	10	3
V3.0	1	0	1	24
V4.0	0.5	-3	0.5	24

Table 3.5.2-1 Difference between Bluetooth Versions

Comparing Bluetooth to Wi-Fi one can see it as comparing night to day. Bluetooth is about creating a PAN connection between many smaller devices, while Wi-Fi is connecting fewer devices into a much bigger local area network (LAN) to get those devices to the even bigger wide area network (WAN) that being the internet. Bluetooth 2.0 has a meager 30ft compared to Wi-Fi's 820ft, which is very important for this project. Wi-Fi has a much higher throughput of 130Mbps compared to Bluetooth's 3Mbps; however this doesn't really matter and in fact hurts Wi-Fi due to much higher power consumption. Wi-Fi has WPA2-PSK and keeping the Service Set Identifier (SSID) for security which prevents people from even seeing the network; compared to Bluetooth's more laid back approach of a password, User Access Control, and "non-discoverable" mode. Both communication standards utilize the 2.4 GHz band, thus neutralizing any differences from there.

3.5.2.1. Bluetooth Module

The current Bluetooth module that best fits the needs of this project and that can work with the Arduino would be the HC-05. This module allows the Arduino to access the 2.4 GHz band and connect to other devices by using the Bluetooth v2.0 standard, as what was shown in table 3.5.2.2-1, the advantages for anything past v2.0 is not worth the drawbacks of that it brings. Any and all important information for this module will be displayed in Table 3.5.2.2-1. The HC-05 also comes in at a reasonable cost of $4.35 from GearBest.com.

Categories	Items	Values
Wireless Parameters	Bluetooth Version	V2.0
	Frequency Range	2.4 - 2.5 GHz
Hardware Parameters	Operating Voltage	3.3V - 5.0V
	Average Current	25mA
	Package Size	28x15x2.35mm
Security	Encryption	128 bit

Table 3.5.2.1-1 HC-05 Data sheet

3.5.3. Zigbee

The Zigbee communication standard is derived from the IEEE 802.15.4 protocol, this protocol was created in order to standardize the way that devices can communicate to each other in a low-rate wireless personal area network. This can be seen as a much more direct competitor to Bluetooth, due to them both is being created in order to deal with the problem of a low powered personal area network. The Zigbee Alliance created the Zigbee standard in order to aid in creating these personal area networks with a low powered devices that can compete with the likes of Wi-Fi and Bluetooth. Zigbee was created in 1998, officially standardized in 2003, and revised in 2006.

Since Zigbee was created in order to accommodate a small personal area network, the features of that original intent is shown. This standard has a define rate of about 250 kilobits per second which is much less than the other two previously mentioned communication standards. The max distance that Zigbee can reach is 100 meters, but this is assuming line of sight between both the transmitting and receiving modules. Since Zigbee mainly operates at the 2.4 GHz ISM band, it provides no difference between Wi-Fi and Bluetooth in regards to its penetration power, and thus hampers its overall range. Zigbee, however, does offer a module that operates at the 900 MHz ISM band, which does help when it comes to allowing the signal to reach farther distance, but it drops the transmission speed from 250 down to 20 kilobits per second. Even though there is a possible sub-GHz module that is offered by this standard, the norm is the 2.4 GHz and thus that is the main focused. The main security feature that Zigbee offers in order to secure itself from any outside intrusion is a 128 bit AES encryption system. This security comes from with no surprise due to the origins of this standard, and doesn't provide any benefits or restrictions compared to Bluetooth; however it is inferior to the security that Wi-Fi can provide.

The network topology that Zigbee offers is no different from Wi-Fi's, mesh and star network. This works well when dealing with a system of many different interacting devices within it, however this project is looking at no more than two interacting parts, so the Bluetooth's model of peer2peer is more preferred. In fact, Zigbee was constructed with the mindset that there would be many different communication modules that would all be talking together in a close environment and through that little system all network traffic will be passed through. Each of these modules would be little nodes that would help handle the overall working load from all of the devices that are connected to the network. This strategy would not work so well in a system that was designed with the mindset of having only two talking components, which hurts the appeal of Zigbee. Zigbee is not normally an IP based networking standard, however there is a variation known as Zigbee IP that allows the use of IPv6.

3.5.3.1. Zigbee Module

The current Zigbee module that best fits the needs of this project and that can work with the Arduino would be the XBEE 24-AWI. This module allows the Arduino to access the 2.4 GHz band and connect to other devices by using the Zigbee standard. Any and all important information for this module will be displayed in Table 3.5.3.1-1. The XBEE 24-AWI also comes in at a much higher cost, compared to the other products that have been shown thus far, of $19.00 from digikey.com.

Categories	Items	Values
Wireless Parameters	Standard	Zigbee
	Frequency Range	2.4 - 2.5 GHz
	Data Throughput	250 kbps
	Indoor Max Range	30 m
	Outdoor Max Range	100 m
Hardware Parameters	Operating Voltage	2.8V - 3.4V
	Average Current	50mA
Security	Encryption	128bit AES

Table 3.5.3.1-1 XBEE Data sheet

3.5.4. Sub-GHz

The three previous communication standards that have been shown in sections 3.5.1 - 3.5.3 have all been focused on the 2.4 GHz ISM band. Now this isn't necessarily a bad thing, but there are other communication standards that come with their own set of advantages and disadvantages by utilizing the 900 MHz ISM band. By using this much lower frequency, these communication standards are able to remain as a much lower power consuming alternative compared to either Wi-Fi or Zigbee, their overall maximum ranges are much higher due to the nature of using a lower frequency, but this comes with the price of a much lower data throughput. This can be seen in Figure 3.5.4-1, this will illustrate the sacrifice of data throughput for a much higher maximum range by comparing Wi-Fi to a Sub-GHz standard. The three communication standards that are going to be shown that operate at these Sub-GHz levels will be Z-Wave, 6LowPAN, and LoRA WAN.

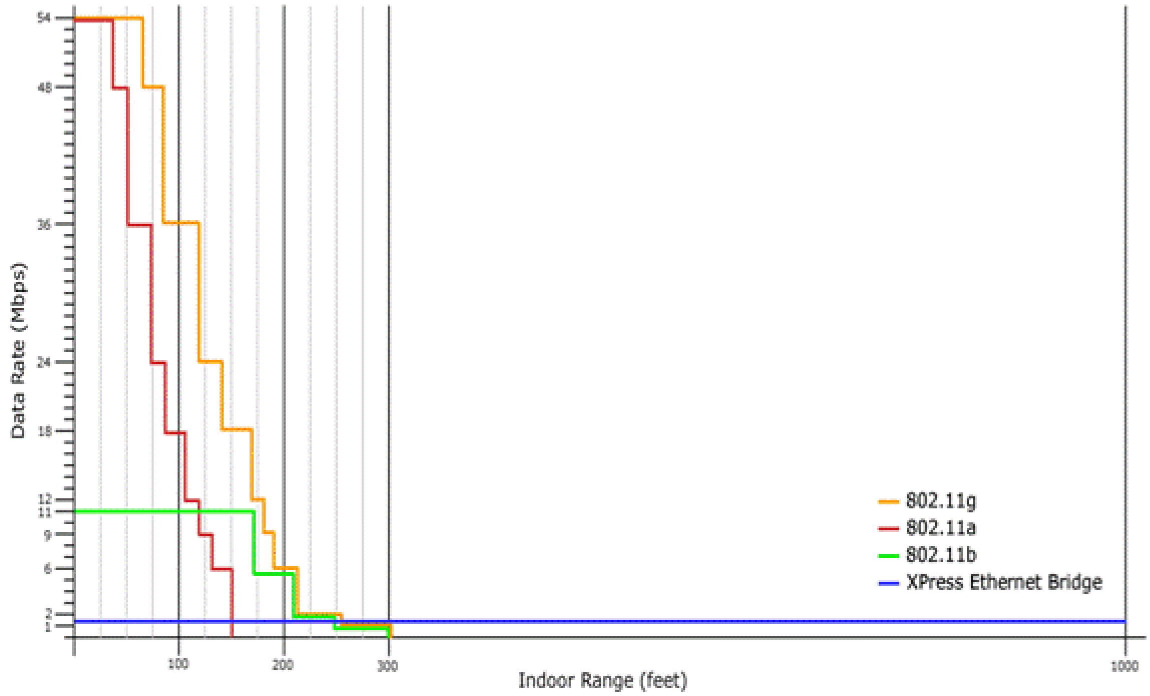


Figure 3.5.4-1 Showing the Difference between Wi-Fi vs. Sub-GHz
(Permission is pending from Digi.com)

3.5.4.1. Z-Wave

Z-Wave is a wireless communication standard that was designed in October 2013 and was standardized in 2014, with its sole purpose being for the use of home automation. The original intent for this communication standard was to develop a way to utilize a low powered communication system that will allow devices in a home setting to be able to talk together in a mesh like network.
This mesh topology network that the Z-Wave creates is able to consist of up to 232 different devices, all talking to each other and even able to bridge multiple networks together to even increase this staggering amount to even higher levels. This feature that Z-Wave provides is an amazing one, however this isn't necessary for a network that will be encompassing only 2 different devices in its network and thus doesn't aid Z-Wave in any way in determining if this is the best standard to use.

Z-Wave was designed to be able to provide a reliable network that is able to meet the needs of devices that are in the home that do not need to send large packets of data. Because of this design intent, Z-Wave is only able to reach a maximum of 100 kilobits per second, which then averages out to 40 kilobits per second. This extremely low data rate, however, is not a truly a bad thing when talking about the scopes of this project, due to there not being a big need to have very high transfer rate since the data that will be sent from the sleeve to the arm will be nothing more than a few kilobytes. Z-Wave does allow its wireless transmissions to reach up to a maximum of 30 meters, but this can be extended by utilizing up to 4 different hops between each node. This range is not very far, and will require additional hardware and thus a further increase of cost in order to increase its maximum range. Z-Wave is now known as an IP based communication standard, however the developers have created ZIPR which will act as a gateway to allow Z-Wave components to connect to the internet. Security for Z-Wave is nothing more than the 128 bit AES encryption that has appeared for both Bluetooth and Zigbee.

3.5.4.1.1. Z-Wave Module

The current Z-Wave module that best fits the needs of this project and that can work with the Arduino would be the Z-Uno. This module allows the Arduino to access the 900 MHz band and connect to other devices by using the Z-Wave standard. Any and all important information for this module will be displayed in Table 3.5.4.1.1-1. The module has not come out yet, however can be pre-order at http://z-uno.z-wave.me/buy/.

Categories	Items	Values
Wireless Parameters	Standard	Z-Wave
	Frequency Range	900 MHz
	Data Throughput	100 kbps
	Indoor Max Range	10 m
Hardware Parameters	Operating Voltage	3V - 5V
Security	Encryption	128bit AES

Table 3.5.4.1.1-1 Z-UNO Data sheet

3.5.4.2. 6LowPAN

6LowPAN is a standard that was developed with the idea to use IPv6 over a low powered wireless personal area network. In a sense, 6LowPan is a low powered version of the Wi-Fi standard for the use of getting devices in a small area to be able to connect to the internet and either send or collect data from other sources. Due to its objective, 6LowPAN is perfect for office and factory environments that require the many devices around these environments to be accessible twenty-four hours of the day.

Since this communication standard was developed so closely with the idea of getting its devices connected to the internet, it makes it a lot easier to get said devices on to the internet due to very similar way that 6LowPAN conducts its packets which closely match that of the World Wide Web. This standard utilizes IPv6's encapsulation and header compression, which then allows the standard to send its packets and receive said packets over the IEEE 802.15.4 networks. All of the nodes within the network are given a 128 bit IP address. This is their address that all the other devices will need to know in order to send their packets to it, and to know where the packets that they are receiving are coming from.

The main focus of 6LowPAN is for energy conservation and having code optimization so that the overall data can be stored in low powered, low memory capacity devices. Because this is the main focus of 6LowPAN, there were sacrifice made in order to ensure that the standard would remain low powered, and because of these sacrifices there were cuts to the overall data throughput that the standard can reach. Unlike Wi-Fi, 6LowPAN cannot utilize the benefits of algorithms and protocols that prioritize data throughput, that focus optimization in the TCP kernel.

6LowPAN's main network topology is the mesh network that focuses on getting many devices all together in a single network and being able to have all of these devices communicate with each other. This is not a benefit for this project, due to having only need of two devices that will be talking together in a single network, and not the many that mesh networks require. The security of this communication standard comes in two different modes: secure mode, and non-secured mode. These two modes are done by the use of an Access Control List.

6LowPAN's frequency range depends on how it is implemented. The standard can either be integrated with Bluetooth to achieve the 2.4 GHz frequency, or be implemented with a standard like Zigbee to utilize the 900 MHz frequency ISM band. Due to this project wanting to use the benefits of the lower frequency, it would be best to use the 900 MHz band. Since 6LowPAN is dependent on how you integrate the standard, its data throughput will depend on that integration.

3.5.4.3. LoRaWAN

The final communication standard that will be address is the Low Power Wide Area Network (LoRaWAN) standard. LoRA is mainly used when it comes to getting small devices to talk together in a small peer2peer network scheme that can be derived from its star topology. LoRA uses both frequency modulation and phase modulation in order to get its message across from one device to the other. The standard uses a "frequency modulation chirp" for its packets to be sent.

LoRaWAN was design with the original intent of creating a wide area network with many different devices that require its communication to be coming from a communication module that has a very low current draw. This standard also wanted to be able to connect these devices that are extremely far apart from each other. From this intent, the LoRa standard is able to reach distances of up to 15 kilometers in a sub-urban area. This is much farther than any of the other standards have been able to reach. In order to reach these kinds of distances, LoRa utilize the 900 MHz ISM band in order to send out its data between the transmitter and the receiver. Since it requires the use of the lower frequency band, it results it a lower data throughput of about 300 kilobits/s, which for this project is just fine.

The security algorithm that LoRa uses in order to keep the network clean of rouge elements is the AES CCM (128 bit) encryption. This security encryption is something typical for the communication standards that use this lower frequency band.

3.5.4.3.1. LoRaWAN Module

The current LoRaWAN module that best fits the needs of this project and that can work with the Arduino would be the rfm69HW. This module allows the Arduino to access the 900 MHz band and connect to other devices by using the LoRa standard. Any and all important information for this module will be displayed in Table 3.5.4.3.1-1.

Categories	Items	Values
Wireless Parameters	Standard	LoRA
	Frequency Range	900 MHz
	Data Throughput	300 kbps
	Indoor Max Range	2000 m
	Outdoor Max Range	6100 m
Hardware Parameters	Operating Voltage	1.8V - 3.6V
Security	Encryption	AES CCM (128 bit)

Table 3.5.4.3.1-1 RFM69HW Module Datasheet

3.5.5. Best Standard

This section will be discussing the benefits of using one standard over the others. They all provide many benefits, but they come with their issues as well. This will be discussed and shown through text and different graphs.

The first issue that should be discussed is the issue of range. The standards that use the 2.4 GHz range have many issues when it comes to achieving very high ranges, whether it is indoors or outside it does not matter. The reason for this issue comes from the fact that the 2.4 GHz frequency has a much harder time when it comes to penetrating different types of materials, such as walls or any other objects that is in the way of the sender and the receiver. Also, since the 2.4 GHz has been tied with the use of Wi-Fi (which being one of the older and more utilize wireless standard), there are many different devices that use this ISM band, thus causing the issue of conflicts with other devices. An example of this is when one is trying to use Wi-Fi on their laptop, and the microwave (a device that uses the 2.4 GHz band) turns on and thus weakens the signal that the laptop has with the wireless router. Due to this penetration and cluttering issues, the lower frequency has an easier time getting through object which grants the ability to have a much farther range than any of the 2.4 GHz standards. This can be seen in figure 3.5.5-1 for the indoor ranges and in figure 3.5.5-2 to see the outdoor ranges. The use of the 900 MHz ISM band for the LoRa communication standard allows it to reach much greater ranges than any of its competitors, making it into a no contest. In fact, the maximum ranges of both Bluetooth and Z-Wave are so low that the graph had to cut off a major portion of LoRa's maximum range in order to show a better looking graph.

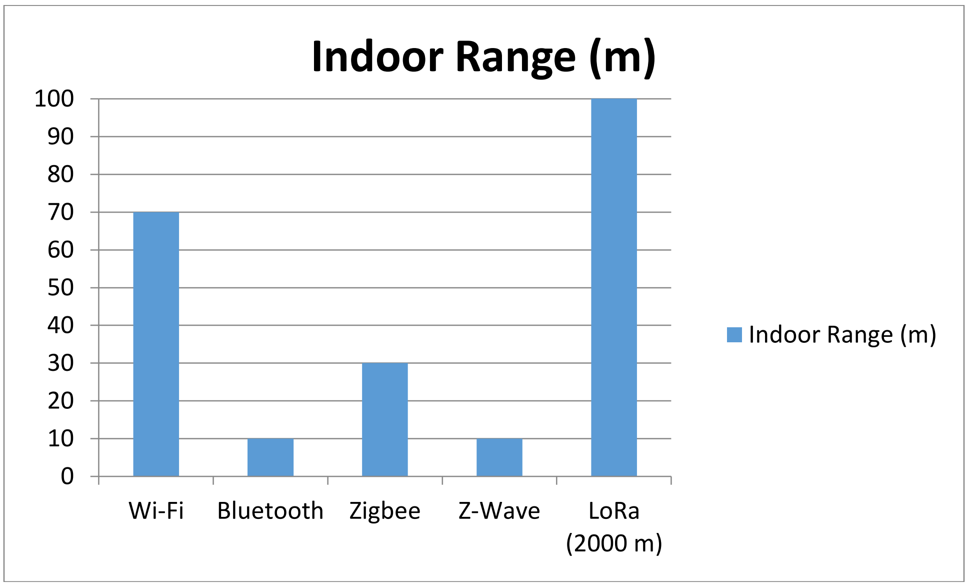


Figure 3.5.5-1 Showing the Indoor Ranges

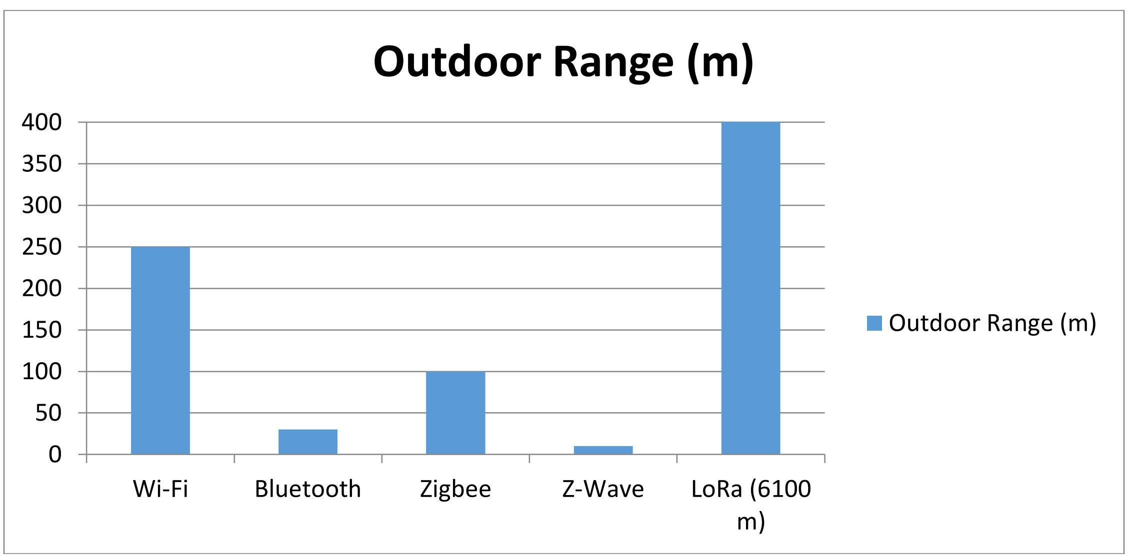


Figure 3.5.5-2 Showing the Outdoor Ranges

The next major issue that should be address is the data throughput of these different standards, to find the one that best corresponds with this project. When dealing with the 2.4 GHz bandwidth, it is a lot easier to send out much higher levels of data than the much lower 900 MHz bandwidth. Due to this, the communication standards that utilize the bigger bandwidth are going to have an advantage in the category of data throughput. This, however, is not as much of an issue as the need to have a very big maximum ranges due to the nature this project. Since this project requires only a one-way communication of data being sent from the sleeve to the arm, and said data is nothing than numbers, the requirement for the data throughput is very low. Due to this, as seen in figure 3.5.5-3, the 2.4 GHz standards are over delivering in terms of data throughput and thus not actually truly aiding in the delivery of the data. The graph had to be cut off a major portion of Wi-Fi's maximum speed in order to show a better looking graph.

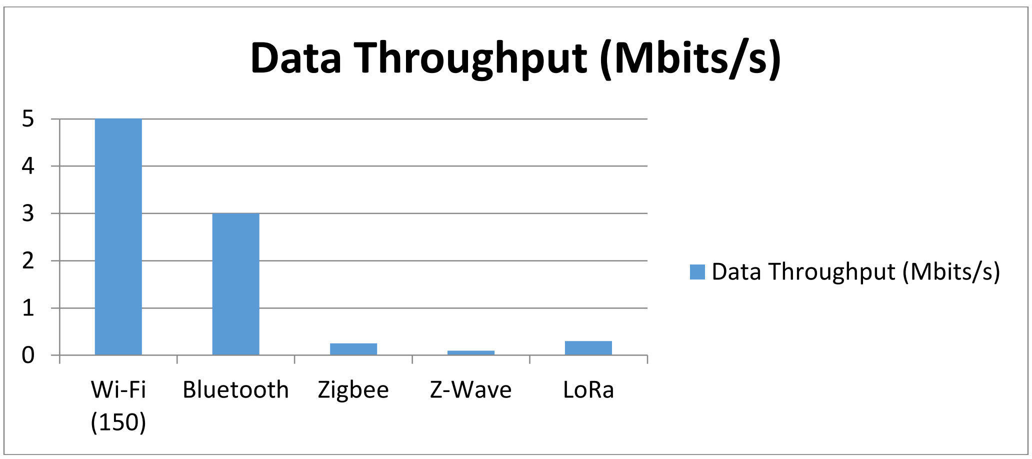


Figure 3.5.5-3 Showing data throughput

Another key issue that needs to be address is the current consumption that these standards draw on the device. Since the sleeve will be mobile by being powered through batteries, it is important to find a standard that prioritizes lowering the amount of current necessarily in order to transmit and receive the data through its wireless communication. By having a higher current draw, it would decrease the amount of time the user can use the sleeve and thus increase the cost of the utilizing the device and also increase the hassle of use by requiring a constant change of batteries. For this particular issue, the standards using the 900 MHz band have a distinct advantage due to needing less effort in order to produce the lower frequency than its 2.4 GHz competitors. The other benefit that the lower frequency using standards have is the fact that the origins of most of those standards was in finding a way to allow for wireless communication in many different low powered devices, and because of this the standards have been built from the ground up focusing on low current draw. However, even with these advantages that the lower frequency standards have, it is actually a very close race between the different current requirements of each of the standards, and that is shown in table 3.5.5-4.

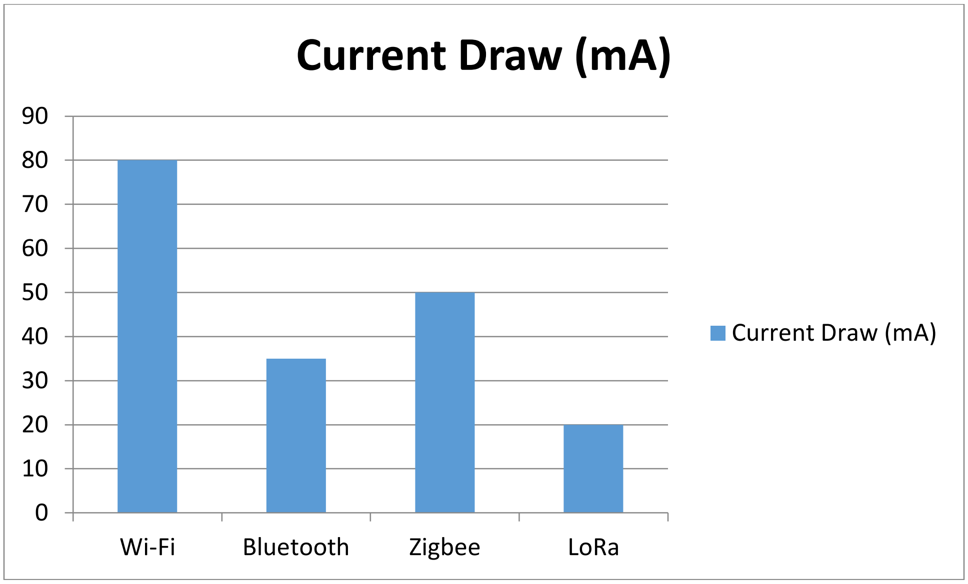


Table 3.5.5-4 Showing the Current Draw

The second to last, main issue that these communication standards need to address for this particular project is the issue on security. Since this project has the idea of being able to aid many different types of people and professions, it is important to have a tightly secured network so that rouge elements will not be able to interfere when the product is being used by its user. By understanding where these standards originated from, there is a clear advantage to a standard like Wi-Fi due to it being a standard that was built in mind of having to be dealing with a lot of important information and being used in a public environment. Due to this mindset, Wi-Fi has created a security algorithm known as WPA2-PSK which is a much more advance than the other standards, which all really on a 128 bit encryption. The securities of each standard can be seen in table 3.5.5-5.

Standard	Security Algorithm
Wi-Fi	WPA2-PSK
Bluetooth	128 bit
Zigbee	128bit AES
Z-Wave	128bit AES
LoRa	AES CCM (128-bit)

Table 3.5.5-4 Security Algorithms

The final main issue that is presented in finding the best communication standard is the network topology that the different standards were developed for. By looking at their respective topology, it will show the environment that these standards require in order to work at their most optimal state. This project requires only two components in its network, that being the sleeve and the arm respectively, and because of this the star and mesh topologies are completely useless for a network with so few talking components. This is where a smaller network topology such as a direct connection between two devices like peer2peer and a star topology that have all the talking components talking to a central hub that then goes to a gateway to allow for internet access is much preferred to the mess that is a mesh network in which all devices are talking to each other. The different standards and their respective network topology is shown in table 3.5.5-5.

Standard	Network Topology
Wi-Fi	Star and Mesh
Bluetooth	Peer2Peer
Zigbee	Star and Mesh
Z-Wave	Mesh
LoRa	Star

Table 3.5.5-5 Showing Different Network Topologies

After analyzing the different standards based off the most important issues for this project, it is LoRa that seems to be the best fit. It has a low data throughput which was shown in figure 3.5.5-3, however the incredible range of 6000 meters in the outdoors, its star on star network topology, and having the best security algorithm (beside Wi-Fi) makes it the clear best choice.

4. Design

Once all the research has been completed, all prospective parts should be well known. An overall idea should also be known when it comes to design and creating schematics for each subsystem. In this section, all design will be laid out from hardware circuit schematics to software class diagrams and flowcharts.

4.1. Power Systems Design

An essential part of the project is the power supply design. Without a functioning power supply providing power where it needs to be at exactly how it needs to be, the arm and sleeve would not work properly. When deciding how power system design will work, two types of consideration must be made: should each component in the system have its own power supply or should each component in the system each be powered through the same source? Taking both into consideration, there are advantages and disadvantages to both.

Each component receiving its own power supply would be ideal for each component. Each component is receiving its exact loading requirements: each is getting the voltage and current necessary for the component to function properly in the system. This approach to the design of the power distribution also has the advantage that each component in the system are drawing power from the same power source, which would prevent other systems from malfunctioning should another component in the system stop working or begin to draw too much. However, should this power design approach be used, providing a power system from each of the components could get cost inefficient and much more space would be taken up by each of the power supplies. Space is an important specification when dealing with the sleeve as the user of the sleeve should not feel burdened to wear it. Another disadvantage to using multiple power sources is that it would limit the design to only the DC implementation for both the glove and the arm power designs, as having multiple AC power sources, which would all be needed to be converted to DC anyway, would have a drastic effect on size, cost, and number of circuits.

Conversely, the second option would be to power each system with their own respective singular power source, in either the form of a AC to DC power supply (AC implementation) or a powerful DC battery (DC implementation). One advantage to using a singular power source for both the sleeve and the arm is that it allows for a more organized, compact area where the power supplies are centered in one area, as opposed to being spread out through each system. With multiple power supplies, wiring could be an issue. So with a more compact, organized area, there will be less wires and design connection errors will be minimized. A disadvantage to using a singular power supply is that each component in each of the systems have different current and voltage requirements, so the need for dropping down the voltage and additional regulation needs to be designed and implemented.

After much consideration, it was decided that having a singular power source for both the arm and the sleeve would be in our best interest. Once that it is decided, it is now time to choose the power supply for each the arm and the sleeve.

4.1.1. Sleeve/Glove Power Design

When designing the power distribution for the glove, it is best to use a DC power source since the user of the sleeve will be wearing the device. Using an AC power source would be troublesome for the user and thus a DC battery will be used. Because we are also implementing a single source power supply topology, the battery must be able to provide enough power to the entirety of the sleeve.

4.1.1.1. Sleeve/Glove Power Supply Selection

With the selection of the battery of the glove, the following design requirements need to be considered:

- Must be lightweight
- Nominal voltage of at least 7 volts

- Must provide 5 volts to sensing and communication modules
- Must provide 3.3 volts to all digital modules
- Size must be appropriate for the wearing of the battery
- Must be able to supply up to at least 1 amp
- Price must be sound

Taking these design requirements into consideration, there are many batteries that can fit into these categories that can provide ample power to the sleeve. After some research, those batteries described in the research sections will be looked into. It is known that there needs to be a number of batteries needed to provide power to the communication and sensor modules. So there will be a need to acquire multiple of each battery to provide this cumulative amount of voltage. Table 4.1.1.1-1 shows a comparison of the batteries researched.

Brand	**Energizer**	**Energizer**	**GMB Power**	**Hunan**
Model	E91	EA91	ER17505M	LP-503562
Classification	Alkaline	Lithium Ion	Lithium Ion	Lithium Polymer
Type	AA	AA	A	Ultra-Thin
Voltage (V)	1.5	1.5	3.6	3.7
Number Needed	4-5	4-5	2	2
Weight (oz)	.8	.5	1.06	.78
Capacity (mAh)	1000	3000	3000	1200
Max Discharge (mA)	2000	1500	1000	1000
Rechargeable	No	Yes	Yes	Yes
Price	$10.32 per 24	$23.40 per 16	$12.95 per 1	$9.95 per 1

Table 4.1.1.1-1: Comparison of Potential Power Supplies for the Sleeve

After taking these batteries into consideration, it is found that although each of these batteries are great to use for this project, the energizer AA batteries will be discarded as options. These two will be discarded because of the limitations that these two types of batteries provide; since size is a big factor when designing the sleeve, having too many batteries will take up too much space, leaving a lot less room for other hardware and well as becoming heavier for the user to wear. Having four to five batteries in a series configuration could weigh between 2 to 4 ounces whereas the other batteries could weigh up to or half as much as the lower bound.

Now the choices in batteries has been narrowed down to two: the GMB A battery and the Hunan flat pack battery. When comparing these two battery types, they have very similar specifications: they both have similar nominal voltages, they both have the same discharge current, they both would require two to reach the voltages needed for the regulators, and they both are rechargeable. Although the LP-503562 flat pack battery has nearly three times less capacity, its ultra-thin size, three dollars less in price, and lighter weight makes it a better choice to use for the sleeve's power supply.

4.1.1.2. Sleeve/Glove Power Supply Circuit Design

In order to design the circuits for the power supply design, it must be known what each subcomponent in the glove system requires in terms of its input voltages and input currents. Once those component input requirements are known, the power can be easily distributed throughout the system using voltage regulators. Table 4.1.1.2-1 provides such information for each component.

Component	Required Voltage (V)	Required Current (mA)
MCU	3.3	7.4
Flex Sensors	5	< 50
Accelerometer	3.3	0.145
Gyroscope	3.3	6.1
Magnetometer	3.3	0.1
Communication Module	5	45

Table 4.1.1.2-1: Input Requirements for Components in Glove System

Texas Instruments Webench: This program is a useful design tool created by Texas Instruments that will support the effort in selecting the voltage regulators and assisting external components needed to supply the glove with power. The Webench tool is a fantastic tool to use as it provides information such as:

- Efficiency
- Distribution of heat
- Part selection
- Cost
- Schematic editing and exporting

5 Volt Regulator: Using the Texas Instrument Webench tool, the regulator that was selected was the TPS562201DDC low quiescent current synchronous buck converter. This voltage regulator has an outstanding max efficiency of 95%, allowing for our batteries to be used to their best potential. The input voltage can range from 7.2 to 8V, which will not cause any issues in the system, and the only need for concern is when the batteries voltage drops under 7V, which means that the batteries needs to be charged. In output current must output anywhere from 0A to 1A. The schematic design for this 5V regulator circuit is shown in Figure 4.3.1.2-1.

This regulator has 6 distinct pins: a VIN, EN, SW, VBST, VFB, and GND pins. The VIN pin is where the input supply voltage is provided. The EN pin is the enable pin which allows the IC to operate, which will be tied to the VIN pin for constant operation. Both the VIN and EN pins will have an input capacitor for stability and input ripple filtering. The SW pin is the switch node connection pin that separates the high and low sides of the internal transistors. This pin will have an inductor on it to provide the switching properties it needs for regulation. The VFB pin is used for output feedback. A resistor divider will be provided to control the output voltage. The VBST pin is used for high side of the internal transistors. This pin will, per datasheet specifications, have a 0.1uF capacitor on it. The GND pin is used for the low side of the internal transistors, as well as the ground for the entire circuit. The equations used to calculate the values needed for each component are found in the datasheet.

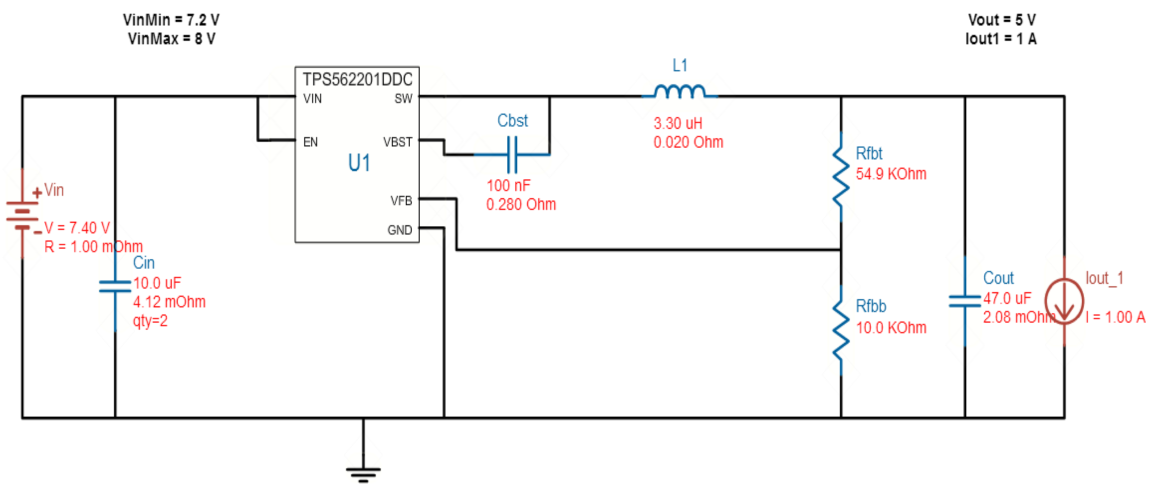


Figure 4.1.1.2-1: 5V Regulator Circuit

Using this 5 volt regulator, the output will be feed to the communications subsystem and the flex sensors to be powered. The 5 volts output will also be sent to another regulator to be stepped down again for the digital components for their power requirements.

3.3 Volt Regulator: Using the Texas Instrument Webench tool, the regulator that was selected was the TPS62152. This voltage regulator has an outstanding max efficiency of 96%, allowing for our batteries to be used to their best potential. The schematic design for this 3.3V regulator circuit is shown in Figure 4.3.1.2-2.
This regulator has 12 distinct pins: an AGND, AVIN, DEF, EN, FB, FSW, PG, PGND, PVIN, SS/TR, SW, and VOS. The AVIN and PVIN are for analog and power inputs respectively, and for the application we are working with according to the datasheet, will be tied together to receive the input supply voltage. The EN pin will also be tied to this pin as the regulator will always be in used. An input capacitor

will be added to this pin to provide stability and input voltage ripple control. The VOS and FSW pins are used for the control loop circuitry and will be tied together per design guidelines to the output. The SW pin is the switch node connection pin that separates the high and low sides of the internal transistors. This pin will have an inductor on it to provide the switching properties it needs for regulation. The SS/TR pin is used for internal voltage reference rise time and will have a capacitor per design guidelines. The PG pin is used for power good, which will have a pullup resistor connected to it. The DEF, FB, PGND, and AGND pins will be grounded as per design guidelines.

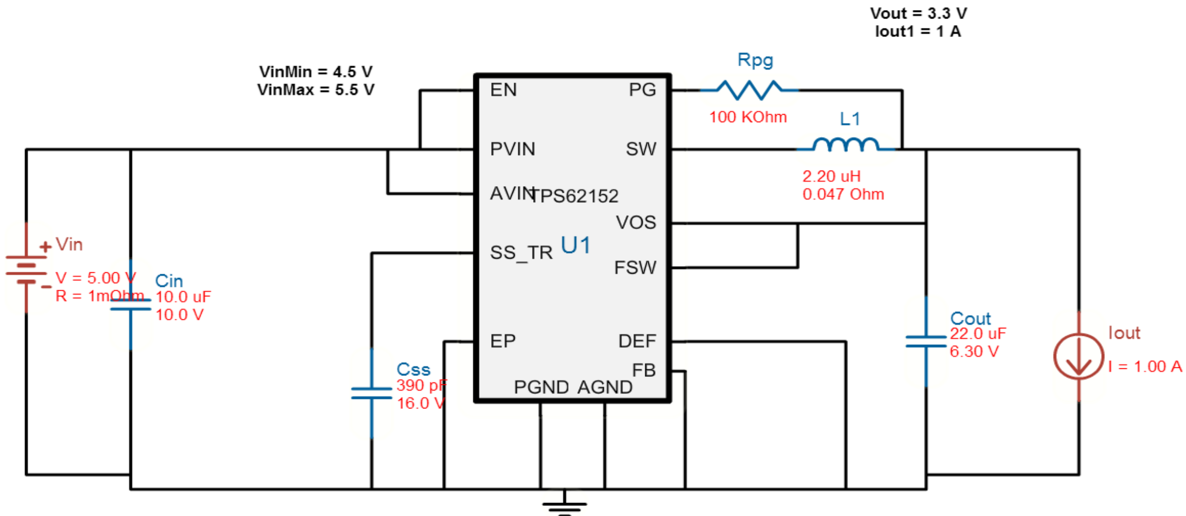


Figure 4.1.1.2-2: 3.3V Regulator Circuit

Using this 3.3 volt regulator, the output will be feed to the digital subsystems that require smaller voltages.

Using two ultra-thin 3.7V lithium polymer batteries, the glove has a good power system going and will not drain too quickly. The two 3.7V batteries will be placed in series and will be feed into the 5V regulator circuit. That 5V regulator circuit will distribute those 5 volts to the subsystems and components that require it. From there the 5V will be routed to the 3.3V regulator circuit to provide power to the digital circuitry. Figure 4.1.1.2-3 shows the glove system power distribution.

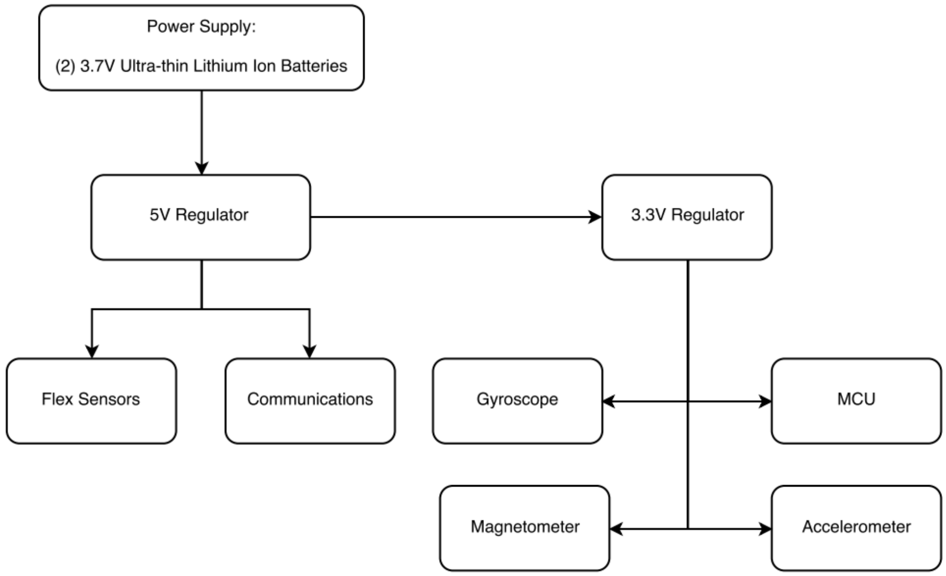


Figure 4.1.1.2-3: Power Distribution for Glove System

4.1.2. Arm Power Design

When designing the power distribution for the arm, either a DC power source or an AC power source can be used. Since the arm will be mounted somewhere stationary, an AC power source could be used, whereas a DC power source would provide more mobility and transportability to the arm. For the sake of the scope of this project, both will be evaluated.

4.1.2.1. Sleeve/Glove Power Supply Selection

With the selection of the power supply for the arm, the following design requirements need to be considered:

- Nominal voltage of at least 7 volts
- Must provide 6 volts to the servo motors
- Must provide 5 volts to sensing and communication modules
- Must provide 3.3 volts to all digital modules
- Must be able to supply up to at least 1 amp to sensing, communications, and digital power
- Must be able to provide up to 20 amps to the servo motors in total.
- Price must be sound

Taking these design requirements into consideration, there are many batteries that can fit into these categories that can provide ample power to the arm. After some research, those batteries described in the research sections will be looked into. It is known that with using a DC battery, to provide enough amperage to the servo motors, at least two of them would have to be used in parallel, whereas using an AC power supply one would not have to worry about the number used as it gets its power from the power grid via and electrical outlet. Table 4.1.2.1-1 shows a comparison of the power supplies researched.

Brand	**Mean Well**	**Mean Well**	**GPR**
Model	MSP-300-7.5	SP-240-7.5	LP-503562
Classification	PSU	PSU	Battery Pack
Type	AC	AC	DC
Voltage (V)	7.5	7.5	7.4
Number Needed	1	1	2+
Capacity (mAh)	-	-	6800
Max Discharge/Output Current (A)	40	32	10.5
Multiple Outputs	Yes	No	No
Adjustable Output Voltage	Yes	Yes	No
Rechargeable	-	-	Yes
Price	$100	$54.84	$47.99 per 1

Table 4.1.2.1-1: Comparison of Potential Power Supplies for the Arm

After taking these power supplies into consideration, it is found that although each of these would be great power supplies for this project, an AC implementation would be easier to implement instead of using a DC battery to power the system. This is because it would remove the need for worrying about the battery dying and requiring it to be charged. It would remove the need to find and purchase a charger for this battery as well. It seems to be a fair trade off to have a constant power source that falls off in supplying power over time for having to use an electrical socket, which can be found nearly everywhere. Possibly in later iterations of this project could include a mobile version that does efficiently use a DC battery for its power supply. Also not using the DC battery provides us with having to only use one power supply instead of having to worry about the possibly of one battery pack failing and not providing the necessary power to the arm.

Now the choice in power supplies has been narrowed down to the two Mean Well power supply units. When comparing these two power supplies, they have very similar specifications: they both have similar output voltages, both require their inputs from an electrical socket, and both have adjustable output voltages. What separates them is their staggering price difference and the fact that the MSP-300-7.5 has the capabilities of outputting multiple outputs of differing voltages, which is a huge advantage as it allows for less voltage regulators to get the voltage at a desired level. The MSP-300-7.5 provides 7.5 and 5V output channels, removing the need for a 5V regulator, but this comes at the price of the cost of the power supply being nearly twice as expensive as the SP-240-7.5. It also has the advantage of providing more output current. Although 40 amps is not necessarily required for how the system is now, the potential for future expansion on the project; these two power supplies would be able to handle future expansions, should we decide to include the forearm as well since more servos would be required.

When making the decision between these two power supplies, it was found that it would be cheaper to drop down the single output voltage from the SP-240-7.5 power supply instead of paying twice the amount of money to have this regulation provided for in the power supply unit itself. So the SP-240-7.5 power supply unit will be chosen for this project.

4.1.2.2. Arm Power Supply Circuit Design

In order to design the circuits for the power supply design, it must be known what each subcomponent in the arm system requires in terms of its input voltages and input currents. Once those component input requirements are known, the power can be easily distributed throughout the system using voltage regulators. Table 4.1.2.2-1 provides such information for each component.

Component	Required Voltage (V)	Required Current (mA)
Servos	6	< 20,000
MCU	3.3	7.4
Communication Module	5	45
Servo Controller	3.3	200

Table 4.1.2.2-1: Input Requirements for Components in Arm System

5 Volt Regulator: Instead of having to design an entirely new 5V regulator circuit, the requirements for the uses of the 5V regulator are the same as the one previously designed. So refer to the 5V regulator design in the previous section for the 5V regulator here.

3.3 Volt Regulator: Instead of having to design an entirely new 3.3V regulator circuit, the requirements for the uses of the 5V regulator are the same as the one previously designed. So refer to the 3.3V regulator design in the previous section for the 3.3V regulator here.

6 Volt Regulator: Using the Texas Instrument Webench tool, the regulator that was selected was the TPS56221 high current synchronous SWIFT converter. This voltage regulator has a range of efficiency from a staggering 98% at lower loading conditions and around 96% leaning towards the upper bound of loading conditions. The input voltage can range from 7 to 8 volts with a nominal input voltage of 7.4V coming from the power supply. This regulator was picked because it can handle high currents ranging anywhere from 0 to 20 amps to provide power to the servos. The schematic design for this 6V regulator is shown in Figure 4.3.2.2-1.

This regulator has 11 distinct pins. The BOOT pin is used for driving the internal FETs. A capacitor must be included on the output of this pin as per design guidelines; a resistor is also placed to help reduce voltages spikes between this pin and the SW pin. The BP pin is a bypass pin and will have a capacitor to ground. The COMP pin is the output for regulator feedback and has a resistor to determine switching frequency. The EN/SS pin is the enable pin, turning on or off the regulator. A capacitor on this pin is recommended as per the design guidelines. The FB pin in the input for regulator feedback and used for reference. The GND pin is ground. The ILIM pin sets the overcurrent threshold for the device; a resistor is place on the output to this pin. The SW pin is the switching node pin for the power conversion. The VDD pin receives the input voltage for the power to the controller and has a bypass capacitor as per the design guidelines. The VIN pin in the input pin for the device.

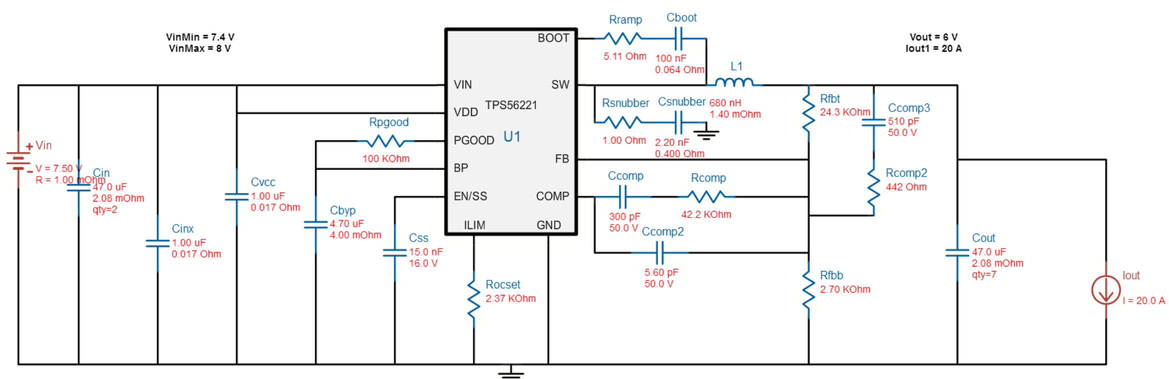


Figure 4.1.2.2-1: 6V Regulator Circuit

Using a 7.5V power supply unit, the arm has a good power system going and has no worries of battery drain out or losing power, so long as the power supply unit is plugged into the electrical socket. That 7.5V output from the power supply will be the inputs for both the 6V voltage regulator circuit to the servo motors and the 5V regulator circuit to the other regulator circuit and the communications and sensing modules. The 5V regulator is then feed to the 3.3V regulator circuit, which will provide power to the digital components of the system. Figure 4.1.2.2-2 shows the arm power system distribution.

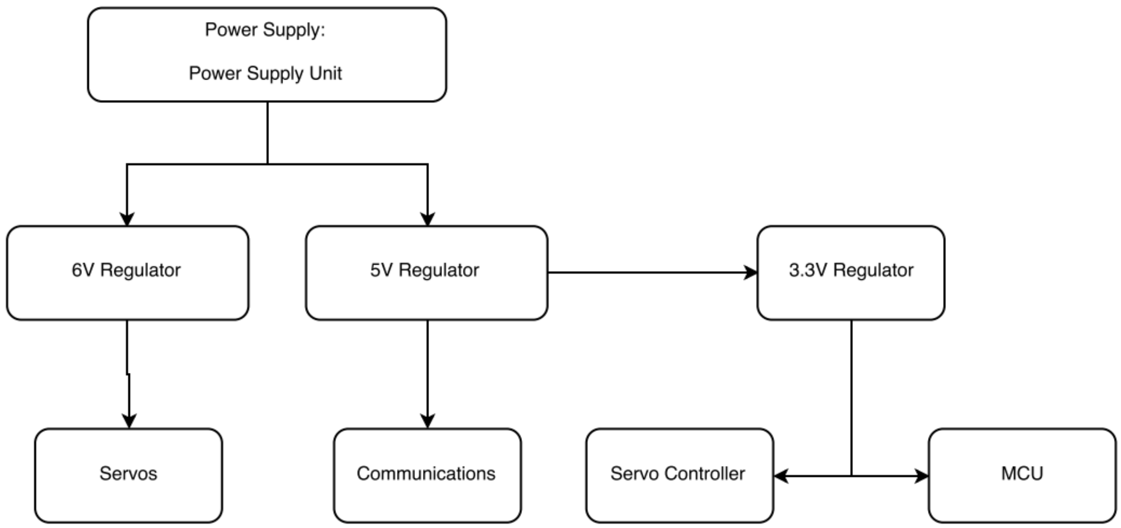


Figure 4.1.2.2-2: Power Distribution for Arm System

4.1.3. Bill of Materials

Parts	Quantity	Total Price
R	11	$ 0.11
C	17	$ 3.80
L	3	$ 1.95
Transistors	0	$ -
IC	3	$ 4.84
7.4V LiPo Battery	2	$ 19.90
Power Supply Unit	1	$ 54.84
	37	***$ 87.50***

Table: 4.1.3-1: Bill of Materials for Power Systems

4.1.4. Power Redesign

During the summer break between the Senior Design 1 and Senior Design 2 courses one of the members of the team received a sponsorship from Hewlett Packard. Because of this sponsorship, the team had to do a redesign of the power system. Below are the system schematics of the redesign, which are shown in Figures 4.1.4-1 and 4.1.4-3.

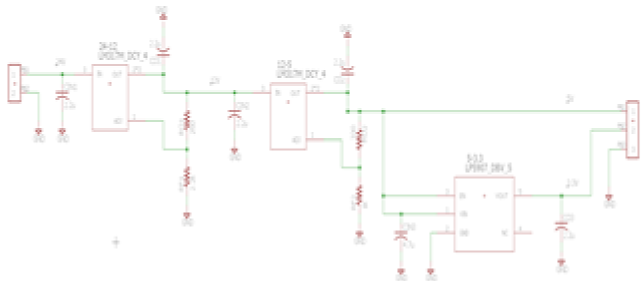


Figure 4.1.4-1: Redesign of Exoskeleton Power Schematic

The corresponding PCB layout of the schematic shown above is shown in figure 4.1.4-2.

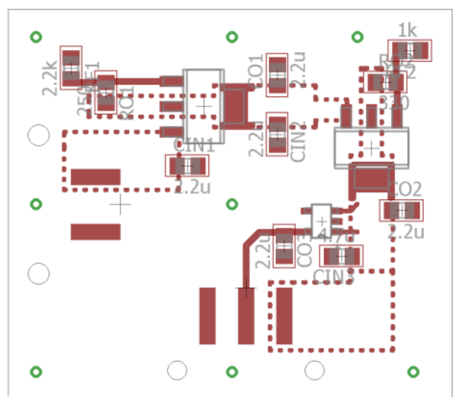


Figure 4.1.4-2: Exoskeleton Power PCB Layout

For the arm power subsystem, the power distribution was also redesigned.

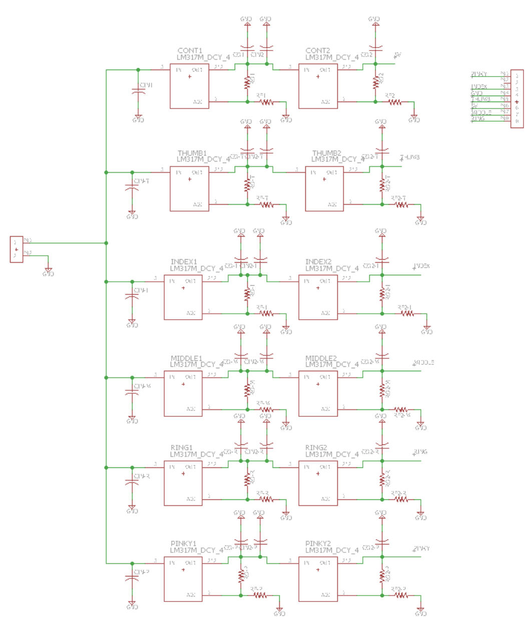


Figure 4.1.4-3: Arm Power Redesign

Its corresponding PCB layout can be found in Figure 4.1.4-4.

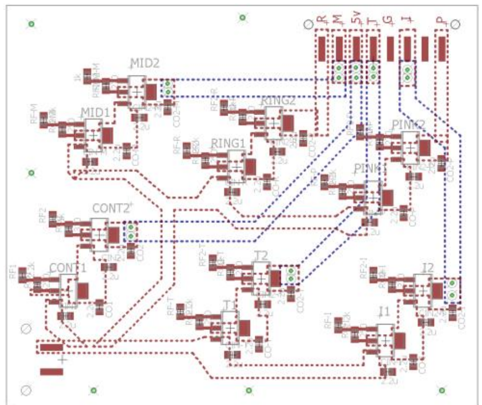


Figure 4.1.4-4: PCB Layout For

4.2. Servo Motor Controller

PCA9685 was picked based on the amount of resources in terms of programming and availability of the hardware. According to the design guideline set forth by the datasheet, pin OE is power through a pull-up resistor if the controller signal is open-drain. In this case, the pin OE would be grounded with a resistor for LOW. Making the pin OE LOW enables the PWM outputs.

The amplitude of the PWM output have is capable of being generating to the magnitude equal to the power supply line connected to the supply voltage pin V_{DD}. The servo motor can still register a PWM input with amplitude of 3 V as command. Each PWM output channel is capable of sinking up to 25 mA and source 10 mA at 5 V, the current draw from the servo motor is yet to be determined. The PWM output channels are still going to be design to have a resistor in series with the signal line to limit the current flow to 20 mA. Utilizing the Ohm's Law, the resistor needed to limit the current flow to 20 mA in series with the PWM output signal is 165 Ω.

Utilizing the power supply line, the supply voltage pin V_{DD} will be connected to the same power supply line as the microcontroller. Additional filtering is not required for this design, since there is internal decoupling capacitor that deals with potential noise.

Two pull-up resistors, R17 and R18, will be used to connect from the I2C pins to the power supply. The value of the pull-up resistors will be determined later putting the other devices that is communicating through I2C as well in consideration. However, the datasheet does suggest referencing section 7 of UM10204, "I2C-bus specification and user manual". Since, I2C communication is the only option for this device to relay data to the controller, pins that are usually used to achieve 4-wire SPI does not exists. The pin DRDY that is used as an interrupt pin is not connected o anything just like the other not to be connected pins on the chip. The grounding pin GNDs are grounded to the ground of the power supply source. The pin SCL and pin SDA is used for I2C communication which will be wired to the I2C bus line of the controller.

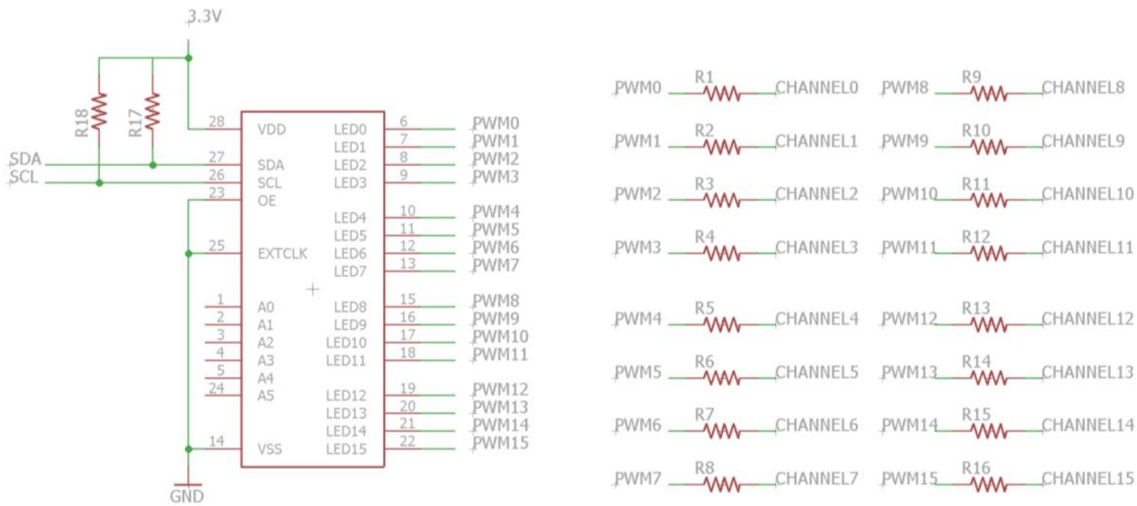


Figure 4.2-1: Schematic of Servo Motor Controller

Although this servo control scheme was used at the end, the implementation was realized with a module instead of a PCB. Instead the focus of control scheme was shifted to a multi-microcontroller design, which realized multiple feedback system for the robotic arm.

4.3. Sensors

The design section for sensors is going to cover the design and additional information regarding the design.

4.3.1. Accelerometer

ADXL345 was picked based on the amount of resources in terms of programming and availability of the hardware. Two decoupling capacitor, C2 and C1, is used to ground both the V_S and the $V_{DD\ I/O}$ to filtered out noise from the power source. At V_S a decoupling tantalum capacitor of 1 µF is used to ground the supply voltage pin to the ground. At $V_{DD\ I/O}$ a decoupling ceramic capacitor of 0.1 µF is used to ground the digital interface supply voltage pin to the ground. If necessary additional decoupling can be done to filter out noise going to the supply voltage pin Vs. adding a resistor that is no larger than 100 Ω in series with the pin V_s, and add a parallel ceramic capacitor of 0.1 µF to the tantalum capacitor after increase the value to 10 µF. Two pull-up resistors will be used to connect from the I2C pins to the power supply. The value of the pull-up resistors will be determined later putting the other devices that is communicating through I2C as well in consideration. Pin CS would be connected to $V_{DD\ I/O}$ as instructed in the datasheet when utilizing I2C. Since, SPI would not be used to communicate with the accelerometer, the pins for the 4-

wire SPI would be utilize accordingly. Those pins not used will not be wired to anything just like the NC pins.

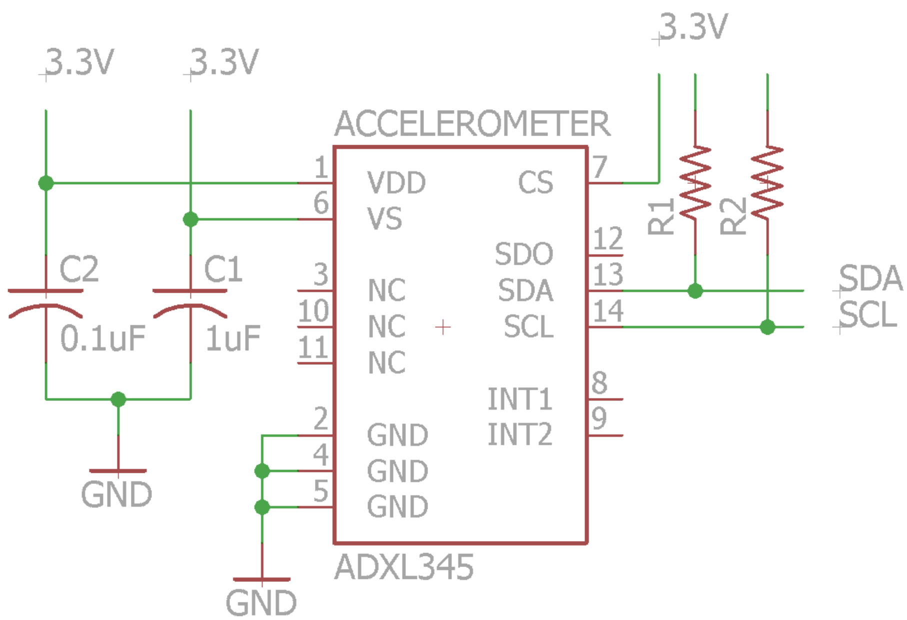


Figure 4.3.1-1: Schematic of Accelerometer

4.3.2. Gyroscope

L3G4200D was picked based on the amount of resources in terms of programming and availability of the hardware. Two decoupling capacitor, C1 and C2, is used to ground both the V_{DD} and the $V_{DD\ I/O}$ to filtered out noise from the power source. At V_{DD} a decoupling ceramic capacitor of 100 nF is used to ground the supply voltage pin to the ground. At $V_{DD\ I/O}$ a decoupling ceramic capacitor of 10 µF is used to ground the digital interface supply voltage to the ground. For this particular set up the V_{DD} and $V_{DD\ I/O}$ are connected together, therefore no additional decoupling capacitor is required for this sensor. If the two were not connected together, then for the power supply V_{DD} in particular additional decoupling capacitors would be needed to filter out noise. The power supply pin V_{DD} would need to be grounded by two decoupling capacitor of value 100 nF and 10 µF to the ground. While the decoupling capacitor of value 100 nF would be needed to ground pin $V_{DD\ I/O}$ to filter out noise. A second-order low-pass filter is implemented on the pin PLL and ground pin. Two pull-up resistors will be used to connect from the I2C pins to the power supply. The value of the pull-up resistors will be determined later putting the other devices that is communicating through I2C as well in consideration. Pin CS would be connected to the single power supply line that pin V_{DD} and $V_{DD\ I/O}$ are sharing as the datasheet instructed when utilizing I2C. Since, SPI would not be used to communicate with the gyroscope, the pins for the 4-wire SPI would be utilize accordingly. Namely the rest of the pin not utilize would be left not connected to any other component in the schematic.

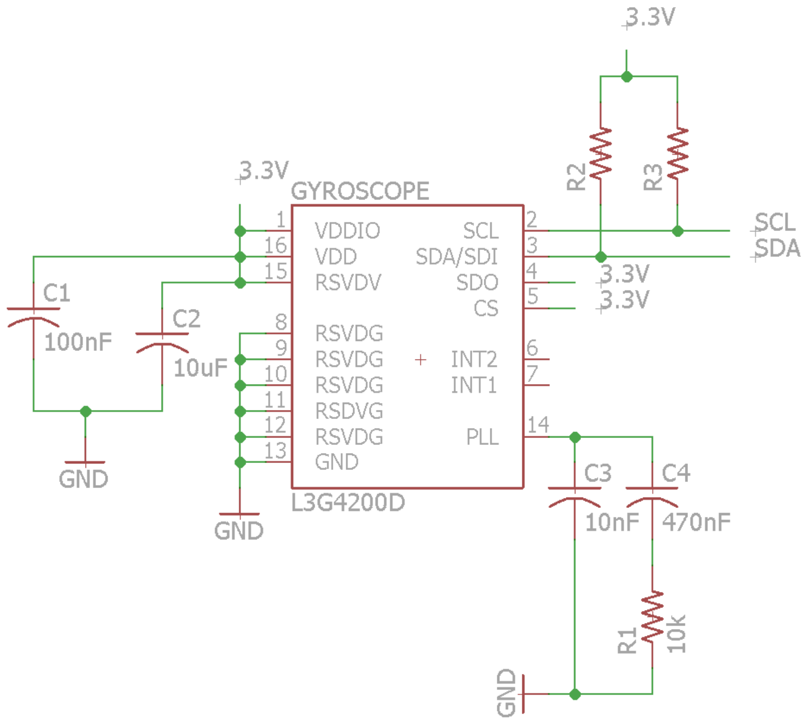


Figure 4.3.2-1: Schematic of Gyroscope

4.3.3. Magnetometer

HMC588L was picked based on the amount of resources in terms of programming and availability of the hardware. Utilizing the single power supply line reference design, the supply voltage V_{DD} and the IO supply voltage $V_{DD\ I/O}$ are both connected to the same line for power. In addition, pin S1 needed to be tied to the same line as $V_{DD\ I/O}$ as per the instruction of the datasheet. For this power configuration only one decoupling capacitor, C3, of value 0.1 µF and type ceramic was needed to ground the power line to the ground to filter out the noise. One of the external capacitor is C1, which grounded pin C1 and is suggested to be a polarized ceramic capacitor near the value of 4.7 µF. While the other external capacitor is C2 which is connecting the set/reset pin SETP and pin SETC, and is suggested to be a ceramic capacitor near the value of 0.22 µF. The datasheet suggested that the two external capacitors to have low ESR characteristics. Two pull-up resistors, R1 and R2, will be used to connect from the I2C pins to the power supply. The value of the pull-up resistors will be determined later putting the other devices that is communicating through I2C as well in consideration. However, the datasheet does suggest the values for the pull-up resistor to be 2.2 kΩ. Since, I2C communication is the only option for this device to relay data to the controller, pins that are usually used to achieve 4-wire SPI does not exists. The pin DRDY that is used as an interrupt pin is not connected o anything just like the other not to be connected pins on the chip. The grounding pin GNDs are grounded to the ground of the power supply source. The pin SCL and pin SDA is used for I2C communication which will be wired to the I2C bus line of the controller.

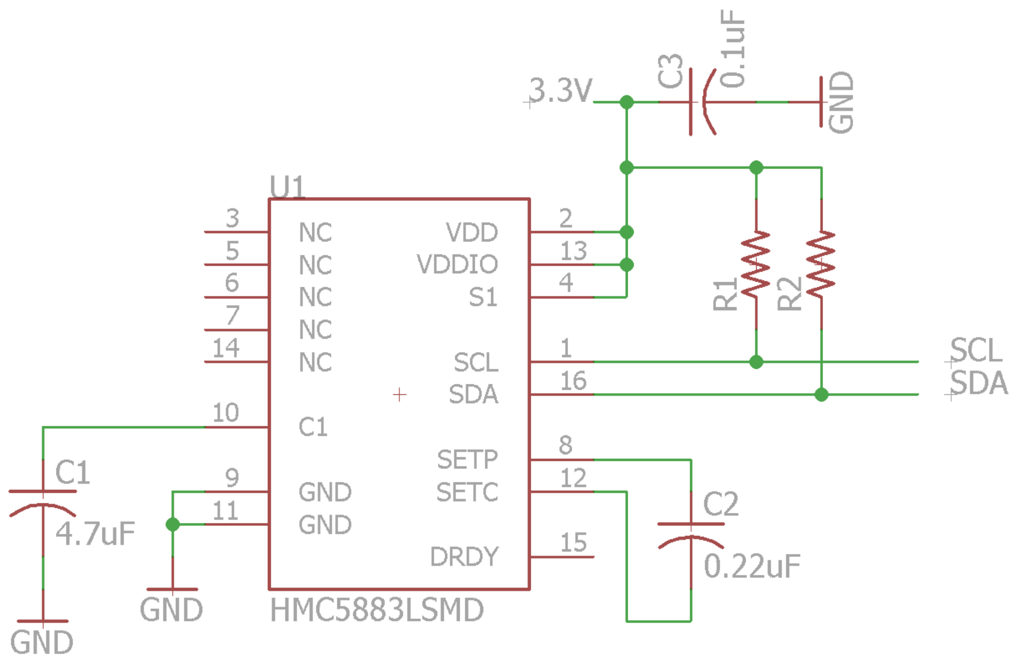


Figure 4.3.3-1: Schematic of Magnetometer

4.3.4. Bill of Materials

This is the total bill for all of the sensors and motors that are going to be required in order to build this project. All of the parts, the amount of each part, and their total price can be seen in table 4.3.4-1.

Sensors	**Item**	**Quantity**	**Price**	**Total Price**
	ADXL345	2	$5	$ 10.00
	L3G4200D	2	$5	$ 10.00
	HMC588L	2	$5	$ 10.00
	Flex	6	$8	$ 48.00
Servos				
	PCA9685	1	$5	$ 5.00
	Towerpro MG996R	6	$10	$ 60.00
	Large Servo	2	$26	$ 52.00
Plastic				
	PLA roll	2	$30	$ 60.00
Total				$ 255.00

Table 4.3.4-1: Bill of Materials for Sensors and Motors

4.4. Microcontroller Design

The Microcontroller is an essential part of the design. We need two, one for the sleeve and one for the arm. In addition to the hardware part of the design, we also need the software portion to be designed. For the scope of this project, an evaluation module such as an Arduino Uno or Mega can't be used. Instead we must design our own board around the chip.

4.4.1. Microcontroller Schematics

This portion of the design will only focus on the aspects regarding the microcontroller. Due to this, the labels on the schematic will show the pins that will go out to the other modules. This includes the communication, which uses the SPI communication protocol. This means using the pins SS, MISO, MOSI, and SCK. In addition to communication module, there will other modules such as the accelerometer, gyroscope, and servo controller. All three of these use the I2C protocol, which uses the pins SCL and SDA.

4.4.1.1. Schematic for Sleeve

The first design that is shown, is the schematic for the sleeve. The chip being used here is the Atmel ATMEGA 328P. This chip was chosen because it required low power, and only needed a source voltage of 5v. The chip is very cheap, and easy to use. As shown in Figure 4.4.1.1-1, the schematic has 6 labels designed for the flex sensors. These are FLEX00 to FLEX05 on pins 23-26 and 19 and 20. The reason for the break was due to the I2C pins, which uses pins 27 and 28. The SDA and SCL I2C pins are connected to the accelerometer and gyroscope sensors. The VCC and GND power signals are obtained from the power supply schematic.

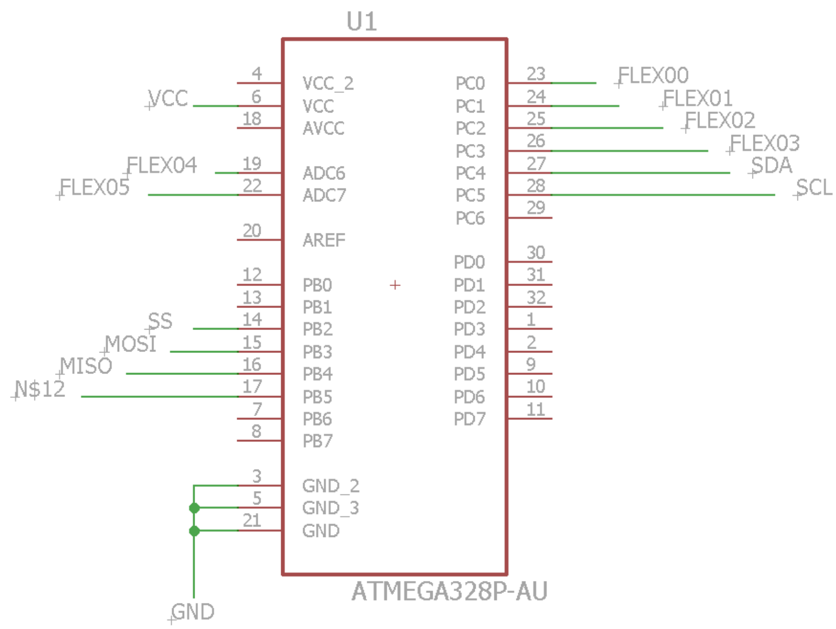


Figure 4.4.1.1-1: Schematic of Sleeve MCU

4.4.1.2. Schematic for Arm

The second design that is shown, is the schematic for the arm microcontroller unit. The chip being used here is the Atmel ATMEGA 328P. This chip was chosen because it required low power, and only needed a source voltage of 5V. The chip is very cheap, and easy to use. As shown in Figure 4.4.1.2-1, the communication pins which use the SPI communication protocol. The SPI protocol uses the pins SS, MISO, MOSI, and SCK. The SDA and SCL I2C pins are connected to the servo driver controller. The servo controller will be driving 8 servos. 5 for the fingers, 1 for the wrist, and two for the elbow. If needed the I2C pins can also be used for another accelerometer and gyroscope to perfectly mirror the X, Y and Z coordinates of both the sleeve and the arm. The VCC and GND power signals are obtained from the power supply schematic.

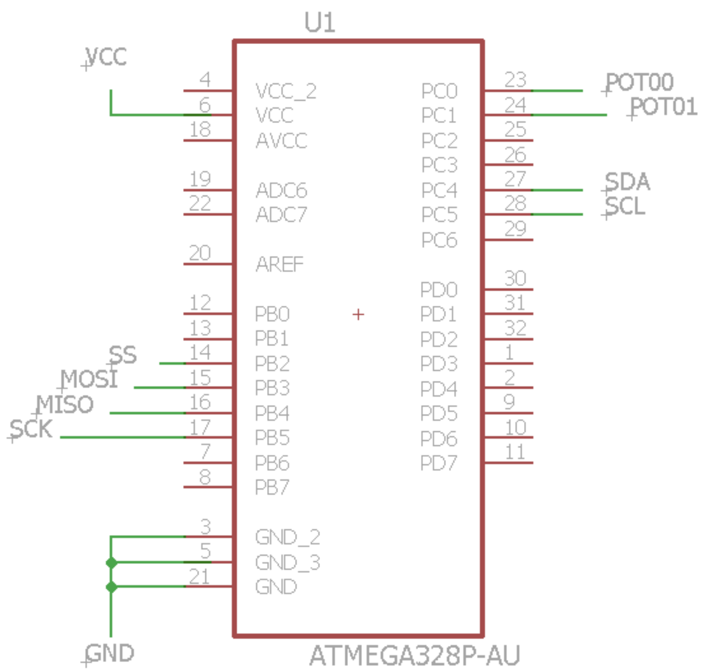


Figure 4.4.1.2-1: Schematic of Arm MCU

4.4.2. Software Diagram for Arm

Just as the hardware must be designed for the arm, so must the software be designed for the arm.

The basic flow for the arm is as follows. First the microcontroller unit is turned on. At this point the servos must be initialized at the zero position. They require an angle from 0 to 180. The angle will be 90 degrees or 1500us for the PWM. This is done for the 8 servos on the arm. The arm will now be in neutral position. At this point the MCU will start receiving data from the other MCU via the RFM69HW. If it successfully receives the data with no packet loss it sends an Acknowledgment signal. This acknowledgment signal lets the other MCU that it has received the data and it is ready to send the next array of data. This is seen in Figure 4.4.2-1.

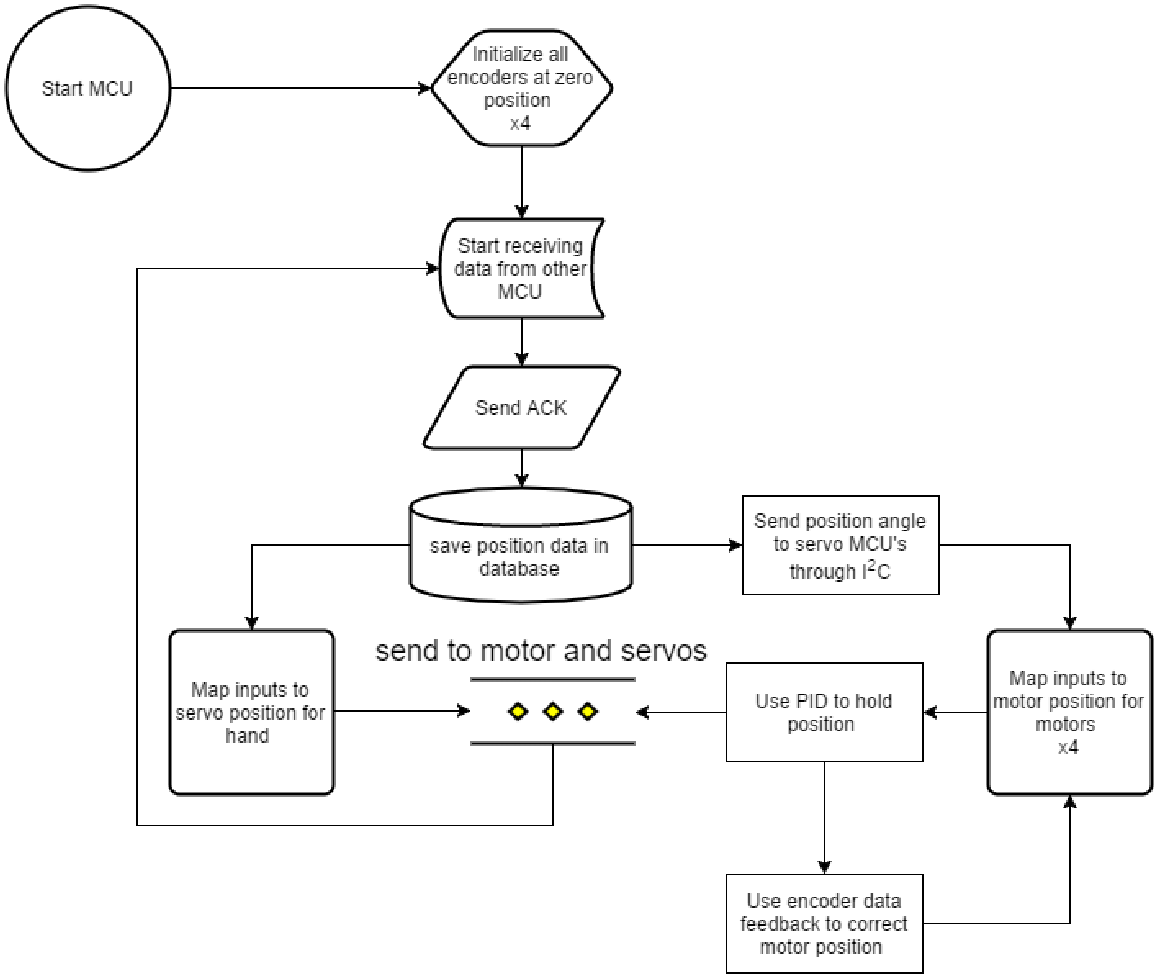


Figure 4.4.2-1: Arm Software Diagram

At this point the data is saved into a database array. From here a function will separate the data into 3 sections. The first section of data belongs to the hand. This means the flex sensors. Flex data is sent into a function that maps the data to a servo positions. The second section belongs to the hand position in regards to the wrist. This will be accelerometer and gyroscope data. This data will be mapped into the servo position for the wrist. The third section of data belongs to the accelerometer and gyroscopic inputs. This data is parsed and mapped to the last two servos. The data is then sent to each servo. The diagram describing the mapping function is seen in Figure 4.4.2-2.

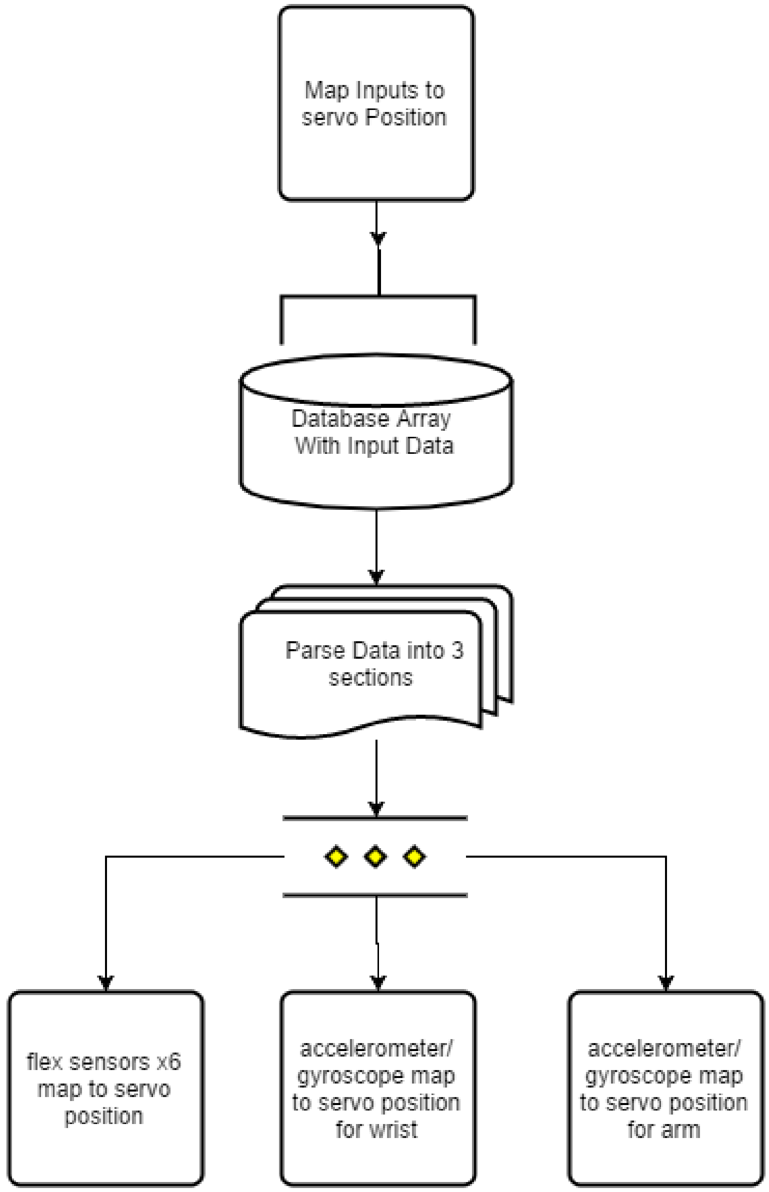


Figure 4.4.2-2: Map Function Diagram for Arm

4.4.3. Bill of Materials

This is the total bill for all of the microcontrollers that are going to be required in order to build this project. All of the parts, the amount of each part, and their total price can be seen in table 4.4.3-1.

Item	Item #	Quantity	Price
Atmega328P	ATMEGA328P-PU-ND	2	$ 3.70
Socket for IC	ED3050-5-ND	2	$ 0.33

16 MHz Crystal	887-1019-ND	2	$ 0.39
Resistors	N/A	2	$0.10
Capacitors	N/A	4	$0.10

Table 4.4.3-1: Bill of Materials for Microcontroller

4.4.3.1. Final Schematic for Sleeve

The final sleeve schematic to be use for PCB layout consist of multiple microcontrollers, which work in together using the Master/Slave communication through I2C. There is a hardware blocks which handles the communication from user to the board, or USB-to-Serial, which utilizes Atmel Atmega16u2. The two sub-level hardware blocks which handles the sensor data of the rotary encoder utilizes Atmel Atmega328p. The main hardware blocks which process all the onboard sensor data and send it over to the other side utilizes Atmel Atmega328p as well. For all the microcontroller used the in-system-programming pins, or ISP pins, are all broken out to each the bootloading of the chip. Whereas, the same is done with the serial pins, or TX/RX pins, to enable programming of the chip.

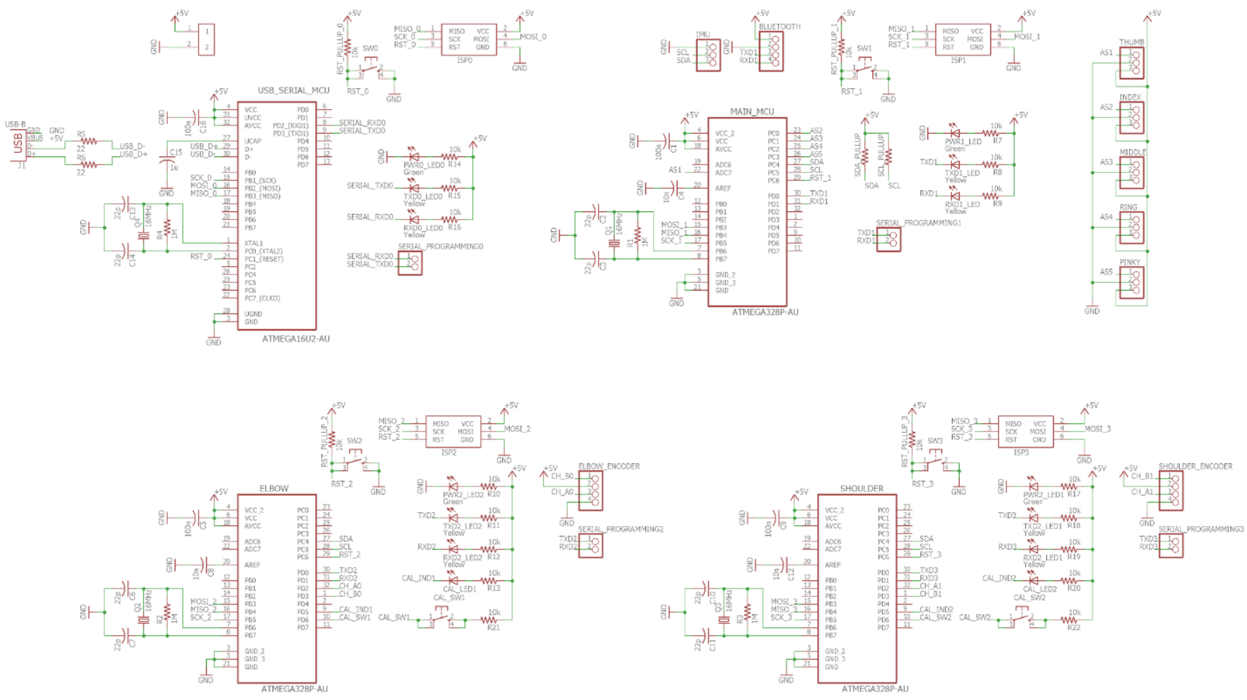


Figure 4.4.3.1-1: Final Schematic of Sleeve MCU

4.4.3.2. Final Schematic for Arm

The final arm schematic to be use for PCB layout consist of multiple microcontrollers as well, which work in together using the Master/Slave communication through I2C. There is a hardware blocks which handles the communication from user to the board, or USB-to-Serial, which utilizes Atmel Atmega16u2. The four sub-level hardware blocks which handles the feedback data of the rotary encoder and forms a loop with the motor control utilizes Atmel Atmega328p. The main hardware blocks which process all the sensor data received from the other side and command the electromechanical system utilizes Atmel Atmega328p as well. In addition, for all the microcontroller used the in-system-programming pins, or ISP pins, are all broken out to each the bootloading of the chip. Whereas, the same is done with the serial pins, or TX/RX pins, to enable programming of the chip.

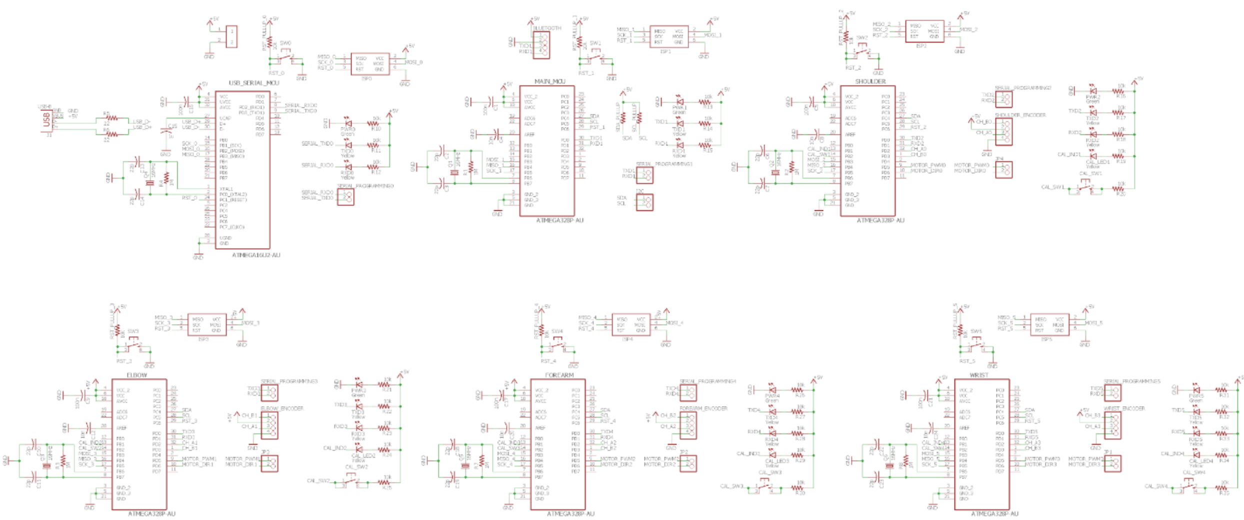


Figure 4.4.3.2-1: Final Schematic of Arm MCU

4.4.3.3. PCB Layout of Schematic for Sleeve

The PCB layout of the final sleeve schematic shown below. With the USB-to-Serial communication hardware block broken out on the top left hand corner. Analog sensor input broken out from the main microcontroller on the top right hand corner. The power source coming from the left hand side near the middle of the board. The main microcontroller hardware block in the bottom middle. The two sub-level hardware block residing on the bottom left hand corner and the right hand corner. All the microcontroller except the communication hardware block communicate with one another through I2C, which was broken out to be use with the gyroscope module that tracks the movement of the forearm and the wrist.

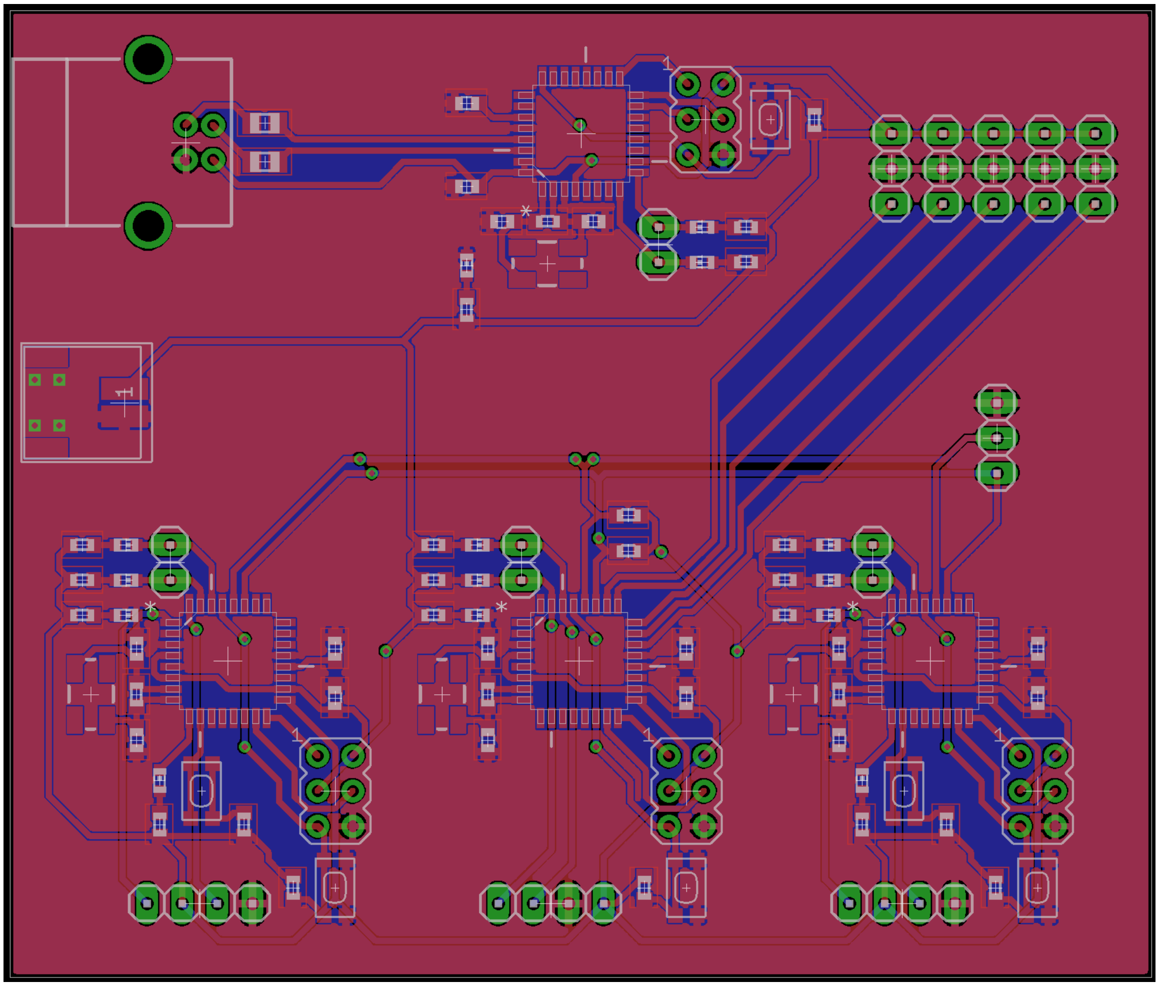


Figure 4.4.3.3-1: PCB Layout for Sleeve

4.4.3.4. Final Schematic for Arm

The PCB layout of the final arm schematic shown below. With the USB-to-Serial communication hardware block broken out on the top left hand corner. Immediately follow by the main microcontroller block on the top right hand corner. The power source coming from the left hand side near the middle of the board. The four sub-level hardware block residing on the bottom of the board starting from the left is shoulder, elbow, forearm, and wrist. All the microcontroller except the communication hardware block communicate with one another through I2C, which was broken out to be use with the servo controller module that handle the hand movement.

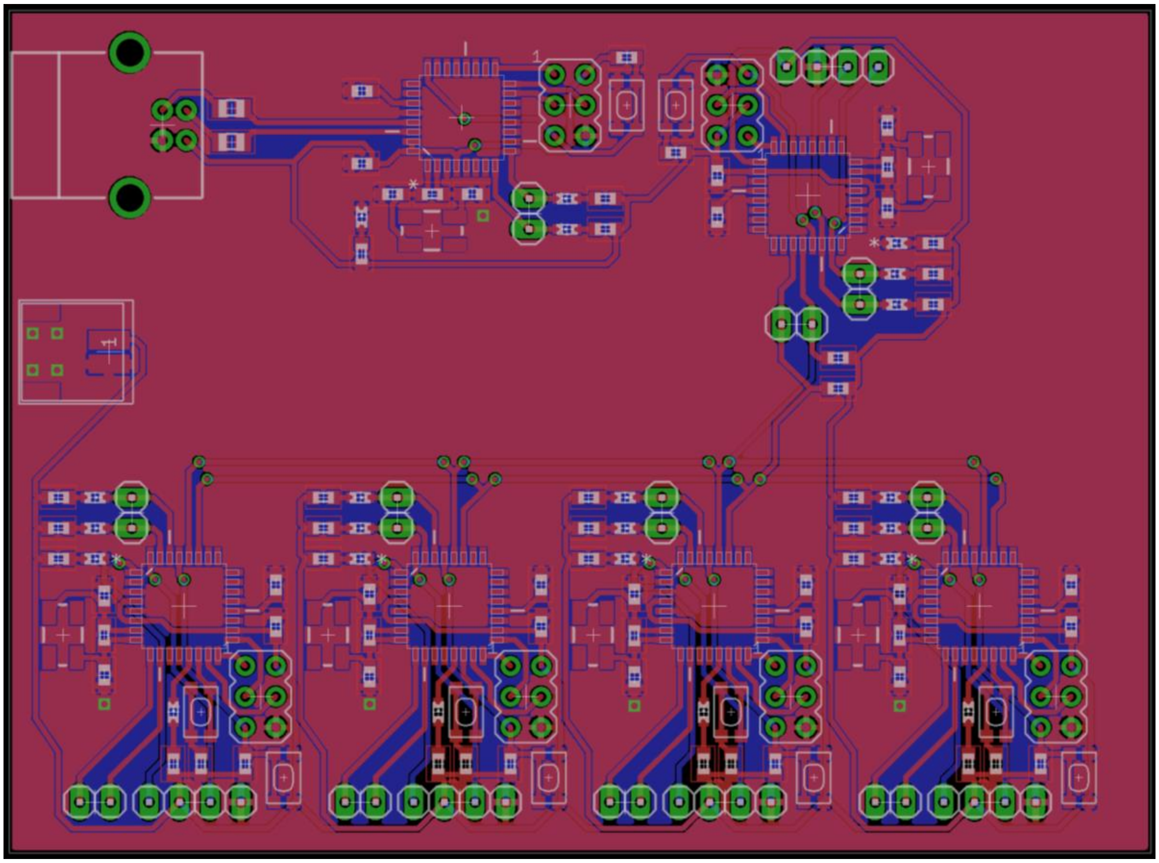


Figure 4.4.3.4-1: Final Schematic of Arm MCU

4.4.2. Software Diagram for Sleeve

Just as the hardware must be designed, so must the software. There are many kinds of software diagrams that can be used. Here an activity diagram is showed. Activity diagrams represent workflows in a graphical way. They can be used to describe business workflow or the operational workflow of any component in a system. Sometimes activity diagrams are used as an alternative to State machine diagrams. Figure 4.4.2-1 shows how the software for the sleeve operates.

The basic flow for the sleeve is as follows. First the microcontroller unit is turned on, then we must calibrate all the sensors. These sensors include the 6 flex sensors, one for each finger (5) plus one for the elbow flexing. Once these flex sensors are calibrated at zero by having the fingers and arm being fully extended, we will calibrate the gyroscope and accelerometer, this is done by having the arm be lying flat on the table that it is being used on, with the palm faced down. At this point we establish communication with the other communication module. Then we start recording all the sensor data and put each value into an array, this array is then put into a database. The first row of the database is sent to the other microcontroller unit via the communication module, and waits for an acknowledgment. Once it receives and acknowledgment it starts sending the next array of signals. And this continues on until we turn of the microcontroller unit.

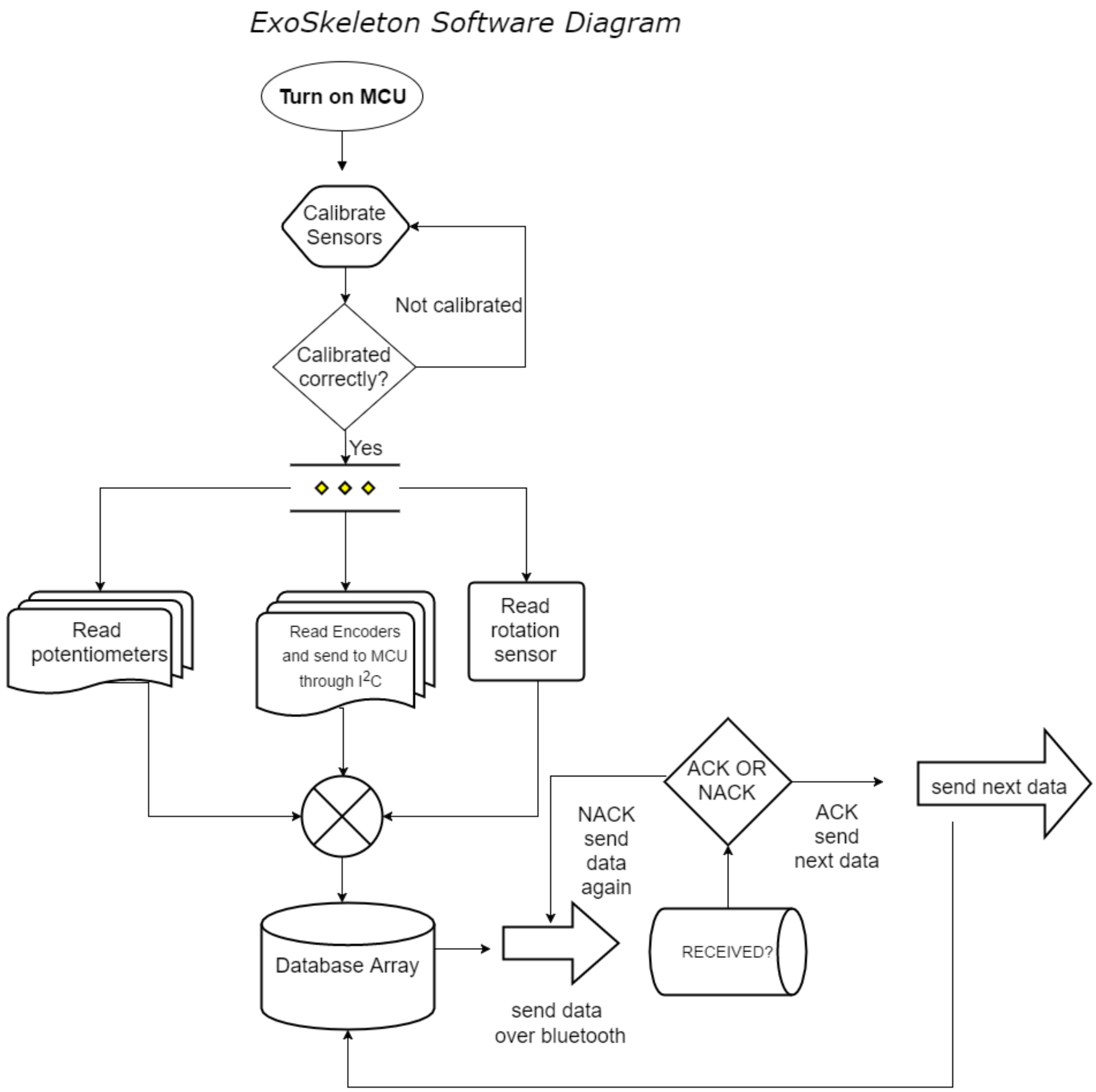


Figure 4.4.2-1: Software Diagram for Exoskeleton

4.5. Communications

For this project, there needs to be a way in order to have the two components communicate with each other. This is where the wireless communication module will come into play. The module that was chosen for this project was the rfm69HW that will be programmed to send the recorded data from the sleeve to the arm so that the arm can mimic the user.

4.5.1. RFM69HW Module

The communication module that will be used is the rfm69HW. This module was chosen due to its ability to follow the LoRa standard which was the best fit for this particular project. This was all discussed in section 3.5.5., as to why this is the preferred communication standard and in section 3.4.3.1. there was the reasoning for choosing this particular module. For this section, it will be discussed on how the module will be integrated into the sleeve and the arm to allow them to communicate. In figure 4.6.1-1, it shows the communication module and its pin layout.

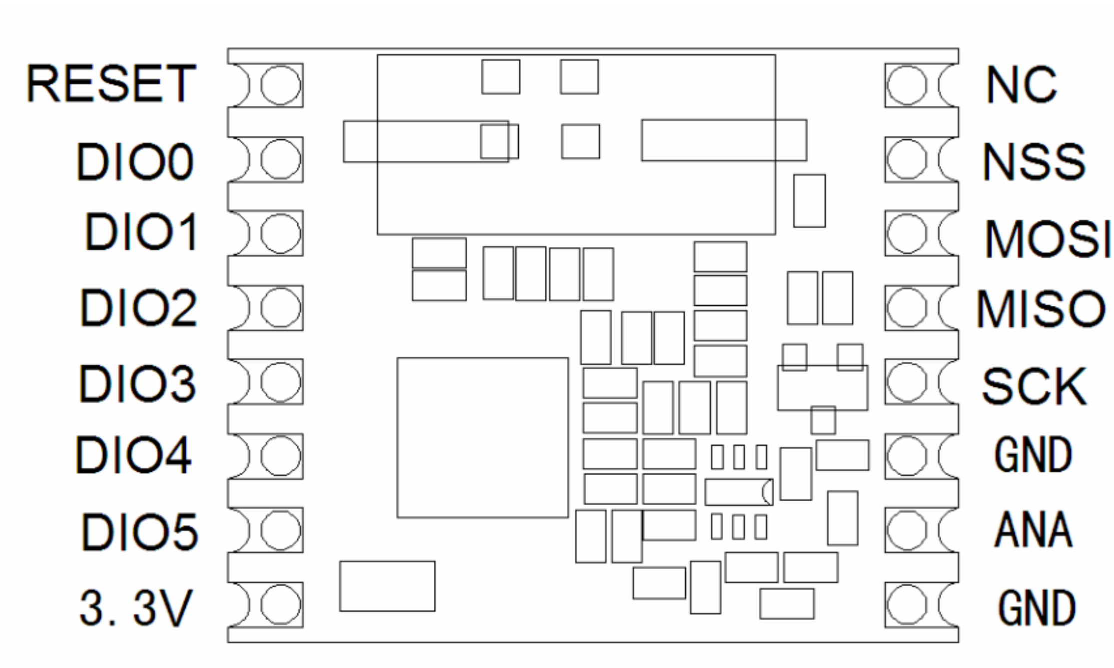


Figure 4.6.1-1 RFM69HW's pin layout

4.5.2. Architecture

This section will describe and show the software architecture of both the arm and the glove by showing the methodology of how they will work and function together.

4.5.2.1. Glove Architecture

The architecture that would best describe the way that the glove will operate is the pipe and filter software architecture. This software architecture would best illustrate the way the glove will be used by a user, which will then use a group of sensors in the glove to record certain types of movements of the user which will then be sent out to another group of sensors that will record another set of movement, and then send that data to the communication module which will send that data wirelessly to the arm. This can all be seen in figure 4.5.2.1-1.

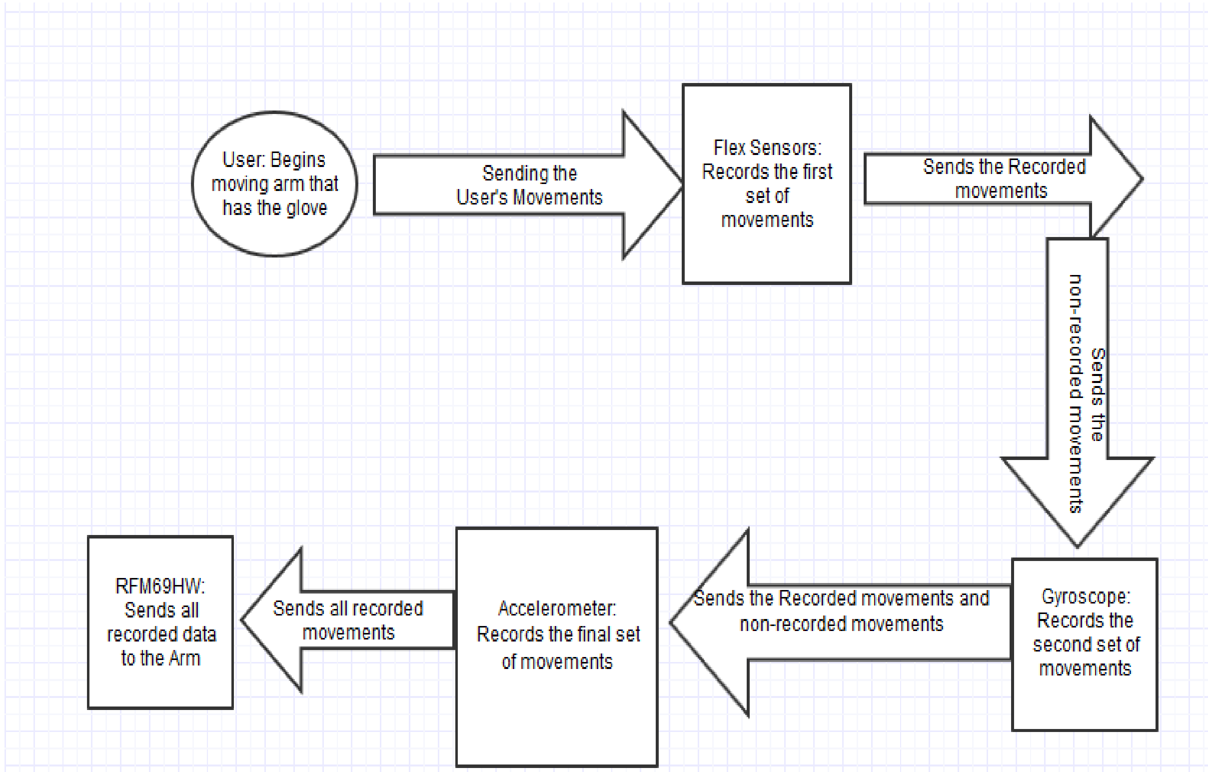


Figure 4.5.2.1-1 Pipe and Filter Diagram for Glove

In this pipe and filter diagram, the pump is the user who is the one responsible to producing all the data that will be soon recorded and sent to the arm so that it can mimic them. The filters are the three different types of sensors that the glove will have installed inside of it to allow for the recording of the movement and the filtering of any un-needed information from the user. Then the final filter is the RFM69HW, which is the wireless communication module that will be receiving all of the data that has been recorded from each set of sensors and then will begin the process of sending that information to the arm so that the arm can begin its mimicking process.

4.5.2.2. Arm Architecture

For the arm, the best software architecture that describes it is the pipe and filter architecture as well. The reason for this is hidden away in the way that the arm will be designed with the way it will pick up the information from the glove and then how it will interpret that information so that it can conduct the actual movements. This can be seen in figure 4.5.2.2.

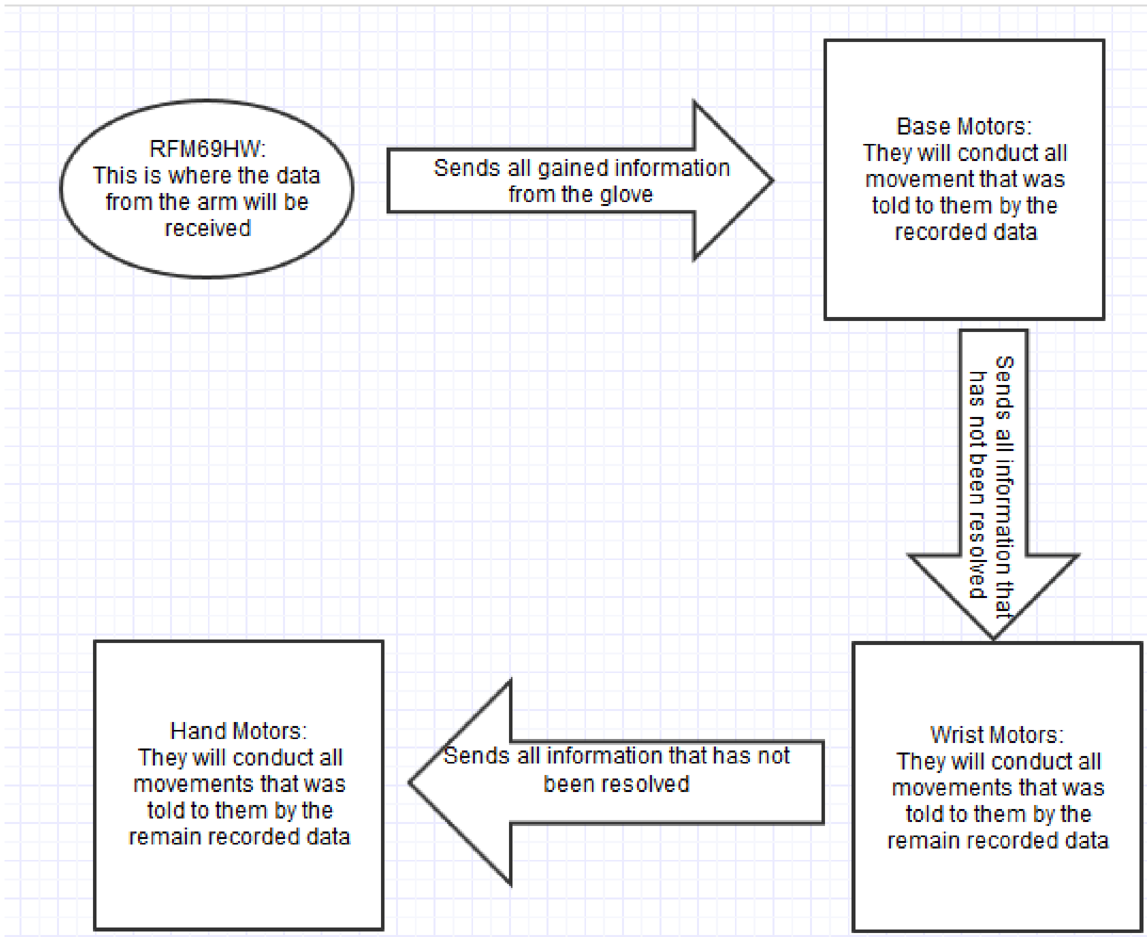


Figure 3.6.1.2-1 Pipe and Filter Arm Diagram

The pump this time is the RFM69HW module, since this is where the recorded data from the glove will first arrive and then be sent throughout the entire arm. The first filter would be the base motor group that will filter out the information for all useful instructions and then carry out those instructions, and then it will send all remaining instructions to the next set of motors. The Wrist Motors will receive the remaining information from the base motors, and then will filter out the information looking for anything that they can actually carry out and they will do so. Any and all remaining information will then be sent to the final group of motors which is the Hand motor group. They will do the same as all of the previous motor groups.

4.5.2.3. Cross Communication

The final software architecture that needs to be discussed is the way both the arm and the glove will communicate with each other. This is important to know how they will communicate, because without a proper way to communicate with each other, there would be no way for the arm to know what it needs to do. The best software architecture that would fit the needs for this communication system would be the Publish-Subscribe model. The reason for this is because there is no feedback coming back from the arm to the glove so there is no way for the arm to ping the glove for information, thus a system like peer2peer and client-server is completely impossible. So the way that the communication can best be shown would be having the glove be a publisher that will send out its information to the arm without any need for a query from the arm. This can be seen in figure 4.5.2.3-1.

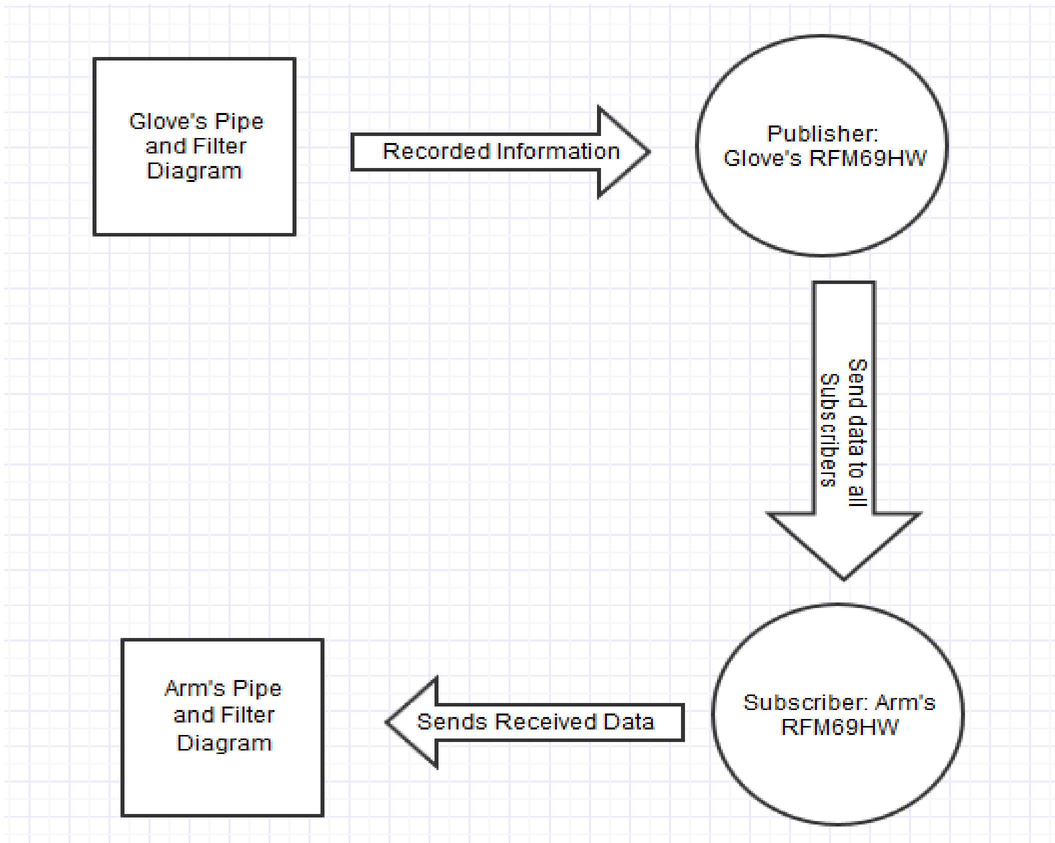


Figure 4.5.2.3-1 Communication Publish-Subscribe Architecture

The Pipe and Filter diagram that was shown in figure 3.6.1.1-1 would first need to record all of the user's movements and convert that into useable information. Once that recording of the data has been completed and all noise to the system has been filtered out, the glove will pipe out the information to the Publisher which would be the wireless communication module RFM69HW. Once all of the data has received it will then send out the data to any and all subscribers, however the only subscriber that the RFM69HW will have is the arm's RFM69HW module and thus only it will receive the needed information. Once the transfer of information is completed, the subscriber communication module will then just pipe out the information it gained to the arm's motor shown in figure 4.5.2.3-1.

4.6. Mechanical Design

There is multiple robotic arm design that is available as Open Source project, providing a wide variety of mechanical solution to this project. Since, the focus of this project is not the mechanical system, it is important to select a mechanical solution that is versatile for electrical system integration. Varys manufacturing method has been considered for rapid prototyping purpose, any method that could possibly accelerate the construction of the mechanical system in the future
.
Two main method of rapid prototyping have been considered, namely laser cutting and 3D printing. Both methods are capable of converting a three-dimensional structure to two-dimensional cross section. For the laser cutting method, two-dimensional puzzle pieces could be piece together to form a three-dimensional structure through cross section bonding. While on the other hand, 3D printing is a process where layer upon layer of two-dimensional cross section is built upon on another to form a three-dimensional structure.

Laser cutting method can utilize different type of materials, with varying thickness, and precision. Some of the materials that can be use with laser cutting are wood, foam, and or acrylic. 3D printing method can utilize different type of materials as well, although this depends on the access to the equipment. The materials that are used by the available equipment are either ABS or PLA.

One of the mechanical designs that were considered for this project was Roy's Arm, which was introduced by Brian Roe in a KICKSTARTER campaign. The three-dimensional structure of this particular mechanical design is made from sheets of wood that were laser cut into two-dimensional structure. This mechanical design was drop, once the realization of lack of supportive resources became clear. There were no mechanical plan to be found and the creator of the project was unresponsive. Otherwise, the lightweight feature of this particular mechanical design would have been very beneficial to the overall system.

The mechanical design that was settled on for this project is the InMoov Open Source 3D Printed Life-Size Robot. Designed by Gael Langvin, a French sculptor and designer, the InMoov humanoid robot is an open source project that offers a mechanical solution to the mechanical system, namely the humanoid arm that this project desires. In addition, a partial arm was inherited from project team that utilized this particular mechanical design in the Spring/Summer 2015 and the access to 3D printers would further decrease the prototyping time required.

5. Project Implementation and Testing

Now that the research and design sections have been discussed, it's time to explore the topic of project implementation and test. To do this, the topic of prototyping must be discussed, this is both for prototyping and for final implementation. Prototypes must be done in both hardware and software, as well as in electrical and mechanical systems that are used here. For instance, the microcontroller unit and software must be prototyped and tested, as well as the power systems and mechanical arm.

An essential part of any project is testing: the validation of all subsystems and components to make sure that the final product will run smoothly and without fail. Most of the problems that will be run into will be during the prototyping stage and that is where most of the bugs and problems need and will be flattened out to ensure the final release works. The tests that will be run will be described here.

5.1. Electrical Hardware

For the electrical hardware for this system, the topics of bread boarding and use of evaluation modules will be discussed. As well as the continuation from prototype to actual implantation will have to be brought up as well.

5.1.1. Prototypes for Electrical and Software Systems

In order to make sure the design is fully functional we must build a prototype of the hardware. This is done so that any design errors will be seen before laying out the printed circuit board and soldering all the connections. To do this, there must use evaluation modules, such as Arduino for Atmel chips or the Launchpad for the MSP430. In order to hookup the electrical connections with the rest of the modules for this project such as sensors, servos, and power, a breadboard must be used to jump the connections.

It is very expensive to get a PCB made, and to find out that there is a design mistake. This is by way of having too small wire traces for power, or finding out that the chip chosen can’t handle the software that is running on it now all the connections must be remade in the software. This is why an evaluation module is used, it makes it much easier to use prototype and make sure everything works.

5.1.1.1. Evaluation Module Test

As mentioned earlier prototyping using evaluation modules is of the upmost importance. Here is where it will be shown how to prototype the modules described in section 4 of design.

The first thing that must be tested is the microcontroller unit, which is the brains of the entire system. The unit in question ATMEL 328P, the evaluation module that uses this is called an Arduino UNO.
First the user needs a computer with the Arduino IDE installed, the computer should preferably be of the Windows OS since all to the designers on this system use Windows systems.

Once the user has the IDE installed, they must attach the Arduino UNO to the computer using a USB cable, the computer will detect it, and the user will select the proper board, under the tool menu. The user will also select the proper COM number for serial communication.

After this the user can upload example code using the file menu. Once the sketch is compiled and uploaded, the user can view the serial output using the serial window.

5.1.1.2. Flex Sensor Test with Arduino Uno Hardware

Now that is established the Arduino Uno is functioning by the previous example code uploaded. It is time to test the flex sensors. These sensors as mentioned in the research section work as variable resistors, the resistance measured changes as the flex angle increases.

In order for the Arduino to understand resistance, there must be another resistor put in place, this way it is possible to do a voltage divider and see the behavior of the flex sensor as a voltage coming into the Arduino Uno. The resistor value in question in this case is 22k Ohms. This value was chose, as many others online chose this same value. Figure 5.1.1.2-1 shows the wiring diagram of how to hook up the Arduino Uno with the flex sensor.

This test only encompasses one flex sensor, later on, there will be a test with 6 flex sensors, with 8 servos attached. But that is for later testing.

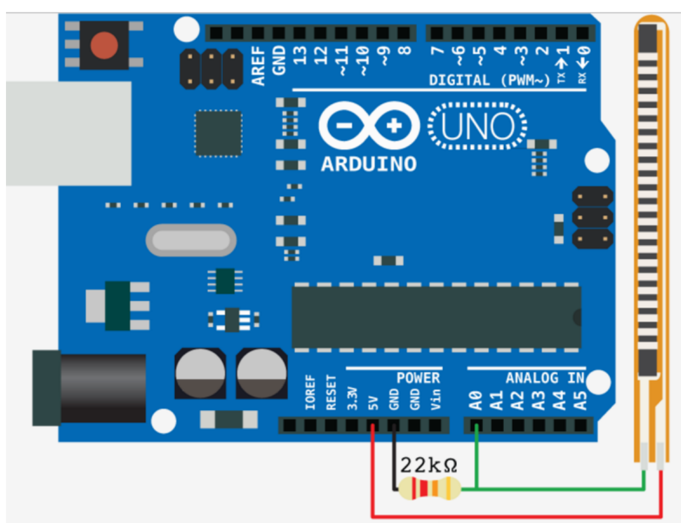


Figure 5.1.1.2-1

5.1.1.3. IMU Hardware Test

The next step of the hardware prototyping and test leads to the accelerometer module. As mentioned in the research section, the accelerometer shows the values of the X axis, Y axis, Z axis get recorded by the module and gets converted by the Arduino. To save pin space, the module only takes 4 pins from the Arduino Uno. These are the 3.3V, GND, and analog pins 4 and 5, which are also the SDA and SCL pins respectively.

As mentioned in the schematic section, the SDA and SCL pins are used to communicate with the I2C protocol. Using this is much more efficient than having a pin for each axis. Not only does it save space on digital pins, but with I2C, you can communicate with virtually unlimited number of modules, as long as there is address space. See Figure 5.1.1.3 for wiring diagram.

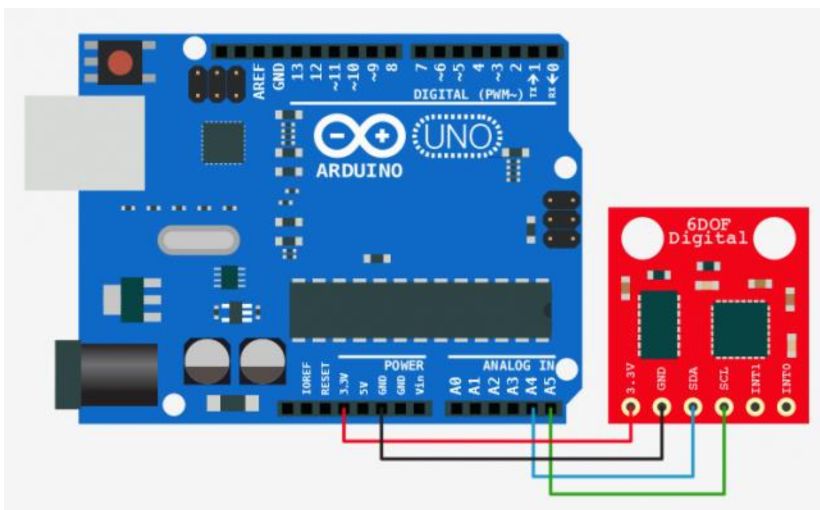


Figure 5.1.1.3

5.1.1.4. Servo Hardware Test

The next hardware module that needs to be prototyped and tested are the servos/servo controller. As mentioned in the design section, the system will be using an Adafruit 16-Channel Servo Driver. This 16-channel driver can drive 16 individual servos separately. And it only takes 4 pins from the Arduino, these 4 pins are 5V, GND, SCA, and SDL.

This means it is using I2C to communicate with this board. Once the full prototype is completed, multiple modules will be connected to the board using I2C, but this is fine, because the Arduino acts as the master while all the other modules act as slaves.

The servo driver will need to have an additional power source in addition to the 5V it is receiving from the Arduino in order to drive all of the servos. The Arduino simply can't output enough current to power the amount of servos that will be used in this project. This is especially true if each servo is using 2.5A. This means that the Arduino wouldn't be able to support even one of the servos, if it is at stall current. Hence why a separate power source is used. This is given from the power supply which is referenced in the design section for power.

Once the Arduino is connected to the servo driver, the next thing that needs to be connected is the servo to the servo driver. The servo needs three pins to operate, VCC, GND, and a PWM line. The servo controller handles all the PWM, so the MCU doesn't have to put out the extra legwork. See Figure 5.1.1.5-1 for wiring diagram.

In the final prototype there will be 8 servos being driven by this servo driver. This is of course fine, because the servo driver can handle up to 16. In fact, with the 6 pins on the right side: GND, OE, SCL, SDA, VCC, and V+, it's possible to attach up to 62 more boards. This is an insane amount of boards let alone servos, 62* 16 = 992. But that's just the max capacity, it would need a huge amount of power and current to power that.

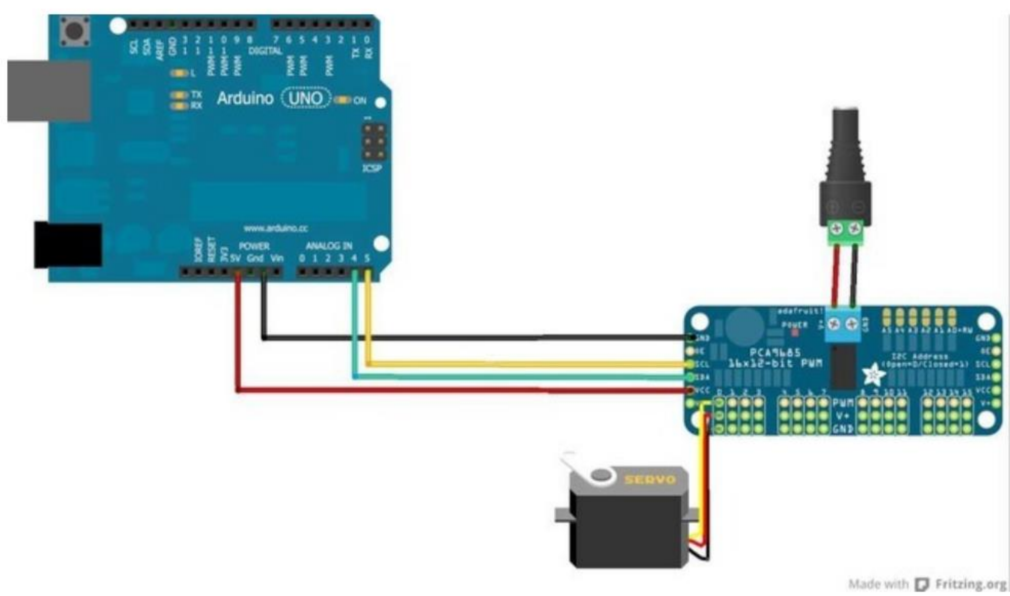


Figure 5.1.1.4-1

5.1.2. Printed Circuit Board

At this point the project prototyping has been completed, so it is now time to design the PCB. It is not necessary to design the schematic from scratch, as it was used to design the prototype, what needs to be done now is the component layout. There are multiple steps in the process of getting a PCB made.

5.1.2.1. Printed Circuit Board Process

First the schematic must be inputted into a CADing software. Then the components need to be layout out on the board using either through-hole components or surface mount devices. The board must go through a design check based on the manufacture's rules for the board. This includes how far a trace can be from the edge, how thick or thin the traces are allowed to be, how many vias, and how big or small they can be.

Once all of that is complete, the design is exported into Gerber files and sent to the board house or manufacturer. Once the board comes back with all the pads in place, it's time to check all the connections, and then solder all the components on.

The user must check all the connections before soldering to make sure all the proper connections have been made. This means checking that all the ground pins and power pins are connected. This is usually done by using a multimeter with the connectivity check feature. Place one probe one side of the circuit, and the other on the other side, and the meter will beep when there is a short between the two points. If all the connections are secure, this ensures that there aren't any board defects.

The soldering can be done in a variety of different ways. First is by hand soldering the fastest of the methods. The limit to this comes when soldering very small components. So the next method is using a hot air gun, this is used when components have no leads. Meaning the soldering iron can melt the solder on them and it can't stick to the board. The hot air gun has its limits as well, as sometimes the part can fly away, or even melt due to the velocity or temperature of the air. This leads to the final method, which is a reflow oven. The user puts all the components in the proper place using solder paste, then it is put through a reflow oven, where the parts and solder paste heat up and the components fall and stick into place.

Of course each method has its ups and downs, hand soldering is the easiest and cheapest, and it gets more expensive from there. Especially when going to companies to pick and place components that can't be soldered by hand, it can cost up to 2 dollars per component, it may not seem like a lot, but it adds up very fast.

5.1.2.2. Printed Circuit Board MCU Bootloading

Once all the components are on the PCB, it is time to bootload the chip. This needs to be done externally, as there is no onboard programmer to flash new firmware on the chip. Evaluation modules have them, which makes them easy to program, whereas on a PCB this must be done separately.

The one downside of bootloading the chip, is it takes up some of the flash memory, so another option to bootloading the chip is using an external programmer. The downside of this, is it will always be needed when trying to upload new code, and it requires another piece of hardware.

The first step to bootload the chip, is to burn the bootloader on the chip. This also requires another piece of hardware, but in most cases it is possible to use an Arduino Uno as an AVR-ISP (in system programmer).

Once this is complete, the user just has to select the right board and programmer from the tools menu, and it only takes a couple of minutes to finish the process. If the bootloading was done correctly, it is now possible to upload the programs to the chip only using the TX, RX, VCC and GND pins.

5.1.2.3. Layout Software

Going back to the layout software, there are many choices that are on the market to layout components on a PCB. Some of these software companies also have board houses or manufactures, in house, so there is no issue converting a design into a physical PCB. There are only a couple of companies that do this, most layout/CADing software's don't have manufacturers in house, but have much more customizable software.

The features of the software vary greatly based on how much the user wants to pay. This includes number of layers, and how much space to layout components, to how smart the algorithms are for auto routing. For this project, the system only needs a PCB with two layers. Which is great for most software as the first two layers are free.

5.1.2.3.1. SunStone

Sunstone is another PCB software that also has their own manufacture in house as well. Their software is free for schematics and board layout. Default the boards are 2 layers at 25 dollars. If the user wants to add another square inch, it costs 3 dollars. This price doesn’t include shipping. This is bad for the user, in case they have a deadline, as the expedited option is a $134, and it still doesn’t include the shipping. Sunstone provides free CAD software for schematics and circuit board layout.

5.1.2.3.2. Eagle

Eagle the most popular PCB CAD software for hobbyist, as it is the most versatile for the price it is at. It can run on most operating systems, and offers all of the functionality needed to make a board. With the free version they limit people to 2 layers, and 3 by 3 inches. But the student version is only $100 dollars which expands the number of layers to 6 and makes the program a lot easier to use. IT also has a simulation add on that one can get if they download LTSPICE, and a BOM exporter to Element14, as they are both owned by the same company.

5.1.2.3.3. Altium

In terms of price Altium is hands down the most expensive on this list. The price for a personal license goes anywhere from $15,000 to $100,000 for corporations. This is for good reason, as the company has developed the software in such a way that it better optimized to use for corporations. They have streamlined the process making it much simpler and easier to make a more advanced board. Altium is also able to do FPGA programming, in program circuit simulation, VHDL, ARM programming, and a dedicated BOM list that exports directly to DigiKey. Also based on reviews, it is much easier to design one’s own components including footprint and package design.

5.1.2.3.4. FreePCB

FreePCB is an open source PCB editor. This software is only available in Windows operating system. According to its website, FreePCB was designed to be easy to learn and use, with the professional quality work.

5.1.2.3.5. KiCad

Kicad is a free program that is open source, runs on any operating system, and has no limit on what it can do. According to user reviews, it is more intuitive to use verses Eagle. It is said to handle vias, and routing a lot better than the competition. The process for building footprints and symbols are apparently much easier, as well as it having a great auto router.

5.1.2.3.6. Circuit Maker

Circuit Maker is another free PCB CAD software. It is actually owned by Altium, but they released it as free to encourage the maker community. It uses the same engine as Altium designer, which gives it a similar experience for the user. One huge issue that people have with it, is that everything is open source, all designs are uploaded to the cloud. This is fine for a senior design project, but not for any propriety intellectual property that a company creates. It is only offered on Windows, but there are unofficial versions of the software on Linux.

5.1.3. PCB Vendor

After schematics are generated, they must be put onto a PCB, or printed circuit board. Because of the complexity and amount of time it would take, it is easier to have a third part vendor to receive and create a PCB for us. The following sections list out and explain the possible PCB vendors available to us for the creation of our PCB.

5.1.3.1. Seeed

Seeed studio is a PCB manufacturer that is based in China. They are the cheapest on the market based on research. They will give 10 2 layer, 5 by 5cm, PCB’s of the same design for $10 dollars. This is incredibly cheap. The only issue is don’t include shipping in that price which makes it cost 10 to 30 dollars more depending on which option the user chooses. If the user chooses to go for the expedited option it is a flat rate of $200 for 10 PCB’s with the same shipping options. Based on the experience of one of the team members, they have delivered PCB‘s at a great rate with competitive pricing, as long as the user doesn’t need it expedited.

5.1.3.2. OSHPark

OSHPark is another PCB manufacturer that is an option. One advantage is that all boards they make are in the USA, and they ship for free. The 2 layer boards are $5 dollars per square inch, with a quantity of 3. The user will get that shipped within 12 days of ordering. They also have 4 layer boards at $10 dollars per square inch, with also 3 copies. This has a 2 week turnaround time.

5.1.3.3. Express PCB

ExpressPCB is another option for getting the PCB made. They have a miniboard service that will create PCB’s at a discounted rate. They will give 2 layer boards at$41 dollars for 3 PCB’s. This is at a max size of 3.8 by 2.5 inches. If the user wants to add a solder mask and silkscreen to those boards, it will cost $61. To get a 4 layer board it costs $81, and the user gets 3 PCB’s up to 8 layers.

5.2. Software Prototyping and Testing

Most hardware would not work without some kind of software. The following sections detail the tests that will be performed for the verification of software functionality.

5.2.1. Flex Sensor Test Software

For the software portion of the flex sensor test, the user must be able to see the values changing in real time using the Arduino Uno. Before attaching the sensor to the Uno, it may be useful to attach a multi to the flex sensor and see if changing the bending angle and see if the resistance is changing. If it does change, it proves that is working.

First the flex pin is defined at zero, as it is put in the analog 0 pin. Then the baud rate is set at 9600, so the serial window can match it in order to display values. In the loop function, the flex position voltage is read with the analogRead() function, and the value is printed using the Serial.print() function. If the value changes in real time on the serial window, then the sensor is working and compatible with the Arduino.

As mentioned in the hardware section for flex sensors. For the integration of multiple flex sensors, and multiple servos, the code will need to be revised.

5.2.2. IMU Software Test

In regards to the IMU, which has both an accelerometer and a gyroscope, there needs to be a software prototype done as well. For this specific module, in order to communicate with it over I2C, the Wire.h library is needed. As well as the address of the module. Luckily the address is predefined. Once this is defined in code, the setup can start. This is where the I2C gets read by the Arduino, and where the baud rate is set up.

In the loop we start the transmission of the register data, which contains the Ax, Ay, Az and Gx, Gy, Gz values. These are the accelerometer and gyroscope x axis, y axis and z axis data values. The transmission starts at 3B which is the starting value to get data, which is given from the data sheet. At this point the MCU confirms there is 12 registers to read from, this is the 6 values that are required to be read. Once each register is read using the read() function, then it is displayed on the serial monitor using the Serial.print() functions. Each Acceleration axis as well as gyroscopic axis of X, Y, and Z are printed to the screen.

5.2.3. Servo Software Test

Along with the hardware for the servo module prototype, there needs to be software to make it run on the Arduino. Here again the Wire.h library is utilized for I2C. Adafruit gave the 0x40 address for I2C. There is also a definition for the servo max and min pulsing. Once the setup sets the baud rate at 9600, and the servos have a defined refresh rate of 60 Hz. The refresh rate is set with pwm.setPWMFreq() function. The loop can start. The loop sends the PWM signal to each servo, with the setPWM() function. Only one servo is being driven in this case. And it also prints which servo it is controlling with what PWM signal value using the Serial.print() function.

5.3. Glove/Sleeve Fabrication and Construction

Now that the research, design, and prototyping for the hardware and software has been completed, it is time to build the prototype for the sensor sleeve. This includes construction of a glove with five flex sensors, accelerometer, and gyroscope integrated in it. As well as sleeve that goes all the way up to the elbow. This will include another flex sensor at the location where the elbow bends and the accelerometer and gyroscope. The sleeve will have the wires integrated with in it. And the main hub of electronics will be on the glove. Since this is for the prototype, the hub will include the Arduino Uno, which is the evaluation module of choice. It will also include the RFM69HW which is the communication module.

5.3.1. Instructions for Glove Build

This section will discuss the construction and build of the glove section of the sensor sleeve. It will go through the equipment needed for the build and step by step instructions.

Equipment Needed:

- 5x 4.5 inch flex sensors
- 1x Arduino Uno
- 5x 22k resistors
- 1x Power source
- 1x accelerometer
- 1x gyroscope
- 1x needle
- 1x thread
- 1x multimeter
- 1x breadboard or protoboard

- 10x jumper wires
- 1x glove

Build Instructions:

1. First we must build the circuit with the five flex sensors attached. We need to do a voltage divider here with the 22k resistors, as the Arduino can only read voltages, and the flex sensors use variable resistance which the Uno can’t use. So we attach the analog pins to the nodes at which the voltage is divided between the resistors as seen in Figure 5.3.1-1.

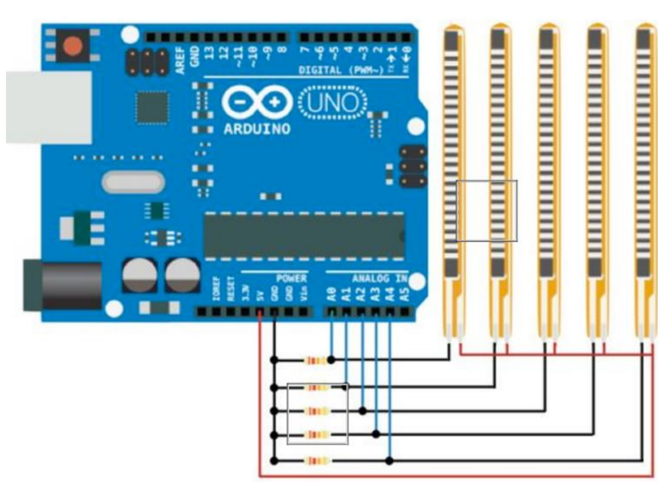


Figure 5.3.1-1: Flex Sensor Prototype

2. The next step is to attach the accelerometer and gyroscope to pins A4 and A5 of the Uno, these are the I2C pins SDA and SCL.
3. At this point, we should check all the sensors to make sure they are working before sewing everything to the glove.
4. Now we must assemble the circuit described in step one on a breadboard or prototyping board. So we basically use the solder the resistors and jumper wires to a breadboard and attach all the necessary pins to the Arduino, while having a common ground also from the Arduino. We are constantly checking for shorts.
5. Now that the construction of the circuit is complete we must attach the leads of the circuit to the flex sensors. There a couple of different ways to do this: we could just use electrical tape, or we could use female crimping terminals. In this case we will use the terminals.
6. To do this use a crimping tool and attach the leads to the female terminals. Once this complete, use terminal housings to finalize the connection. Do this for all 5 of the flex sensors.
7. To keep the flex sensor connections secure, as they are very fragile we need to use a heat shrink tubing. First we slide the shrink wrap over the lead

housing, and then once it is over the desired portion, we use a hot air gun to shrink the tubing.
8. At this point we test each flex sensor with a multimeter to make sure they are still functioning.
9. Attach Velcro pieces to each terminal housing by wrapping it each section.
10. Use Figure 5.3.1-2 to mount the flex sensors to the glove.

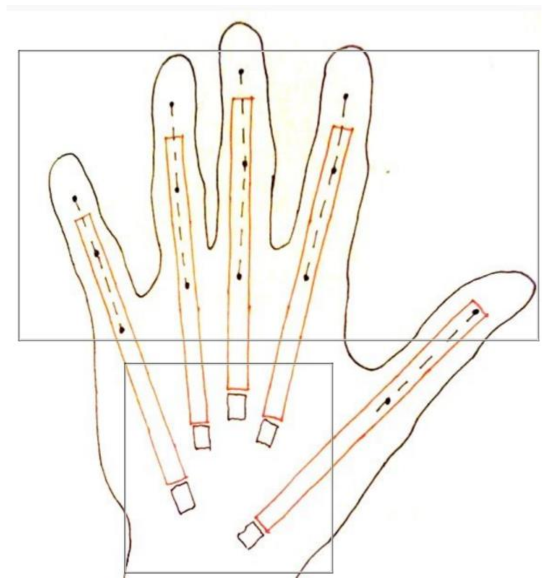


Figure 5.3.1-2: Flex Sensor Mounting

11. At this point we connect the five flex sensors, accelerometer and gyroscope to the Arduino analog and I2C pins.
12. Open the Arduino IDE on a computer and start a new script.
13. Use the analog read() function to get the values of the flex sensors. Then use the Serial.println() function to display the values to the serial monitor.
14. Use the Wire.h library to read the I2C values, and the Serial.println functions to display the values on the serial monitor.

At this point the glove construction is complete. We must now discuss the construction of the sleeve.

5.3.2. Construction of Sleeve

In this section we will be discussing the construction of the rest of the sleeve. This includes the other accelerometer and gyroscope as well as the last flex sensor. We will use a large section of cloth to create the connection for the sensors.

Equipment Needed:

- 1x Flex sensor

- 1x accelerometer and gyroscope
- 6x wires
- Cloth
- Multimeter
- Sweat band

Build Instructions:

1. Use the multimeter to check the flex sensor.
2. We must attach the leads of the circuit to the flex sensors. There a couple of different ways to do this: we could just use electrical tape, or we could use female crimping terminals. In this case we will use the terminals.
3. To do this use a crimping tool and attach the leads to the female terminals. Once this complete, use terminal housings to finalize the connection. Do this for all 5 of the flex sensors.
4. To keep the flex sensor connections secure, as they are very fragile we need to use a heat shrink tubing. First we slide the shrink wrap over the lead housing, and then once it is over the desired portion, we use a hot air gun to shrink the tubing.
5. At this point we test each flex sensor with a multimeter to make sure they are still functioning.
6. Attach Velcro pieces to each terminal housing by wrapping it each section.
7. At this point we will attach the flex sensor to a sweat band by using the Velcro.

Now we attach the accelerometer to the sweat band by using the sewing kit.

5.4. Arm Fabrication and Construction

The robotic arm chosen for this project, the InMoov humanoid robot, is shared under the Creative Commons-Attribution-Non-Commercial 3.0 license. This meant that the mechanical system that is relevant to this project from InMoov is free for this project to remix, transform, and build upon. The humanoid arm mechanism is what would be taken, utilized, and modified for this project. As of now the humanoid arm mechanism being utilize for this project includes the hand, forearm, and bicep.

The general fabrication of the humanoid arm mechanism can be 3D printed using either ABS or PLA as raw material. The 3D printing files of the format STereoLithography, STL, can be obtained from the InMoov's website. 3D printer print time can be obtained through the TI Innovation Lab, CEL Lab, and or other manufacturing lab on campus. For the TI Innovation Lab student are allowed to print up to a certain amount for free. If the student wishes to print more prints, then student would need to provide the print material. Other manufacturing lab with the exception of CEL Lab would charge a fee for the prints. The CEL Lab is the only lab that provides free 3D printing time without charging fee for the materials used.

The general construction of the humanoid arm mechanism would be based on the construction guide provided on the InMoov's website. As of now, with the current set of the mechanical structure is a mix of parts printed in both ABS and PLA material. When it comes to adhering parts printed using ABS material, Acetone would partially dissolve and link the two or more parts together. Multi-compound glue such like epoxy can also be used to bend two or more parts printed using ABS material together. Whereas, when it comes to adhering parts printed using PLA material, PLA glue or multi-compound glue such like epoxy can be used to bend.

5.4.1. Hand

The hand is composed of 10 STL files, of which each STL files contain one or more components are listed within. The thumb file contains 6 different components that allow the finger to have 2 degrees of freedom. The index finger file contains 6 different components that allow the finger to have 3 degrees of freedom. The majeure finger file contains 6 different components that allow the finger to have 3 degrees of freedom. The ring finger file contains 6 different components that allow the finger to have 3 degrees of freedom. The auriculaire finger file contains 6 different components that allow the finger to have 3 degrees of freedom. The bolt entretoise file contains 6 different components that locks palm structure together. The wristlarge file only contains 1 component. The wristsmall file only contains 1 component. The coverfinger file contains 5 different components that cover up the connection point between the fingers and thumb to the palm. The topsurface file contains 3 different components that cover up the back of the palm.

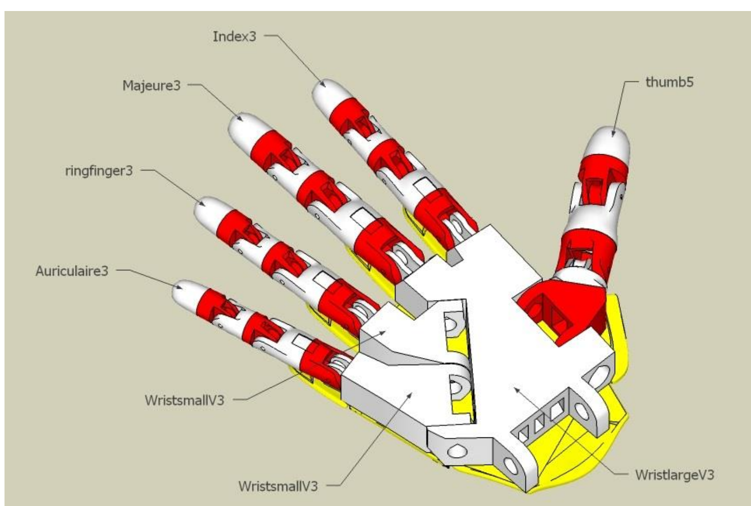


Figure 5.4.1-1: Palm of 3D Printed Hand

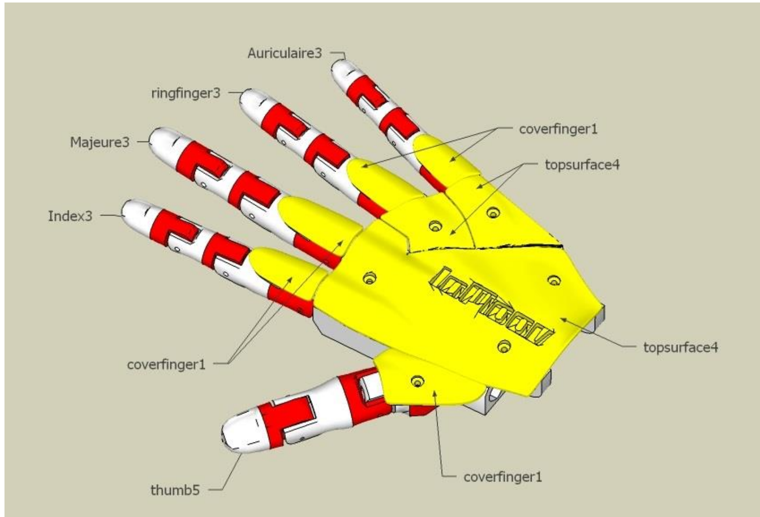


Figure 5.4.1-1: Top Down of 3D Printed Hand

5.4.2. Rotation-Wrist

The rotation-wrist is composed of 5 STL files, of which each STL files contain one or more components are listed within. The leftcableholderwrist file contains only one component that organizes the tensioning cables. The wristgears file contains 3 components that are going to allow the servo motor to rotate the wrist. The leftrotawrist file contains only one component that is going serve as the bottom portion of the servo motor mount for the wrist. The leftrotawrist2 file contains only one component that is going serve as the top portion of the servo motor mount for the wrist. The rotawrist3 file contains only one component that serves as the connection join for the hand to the wrist.

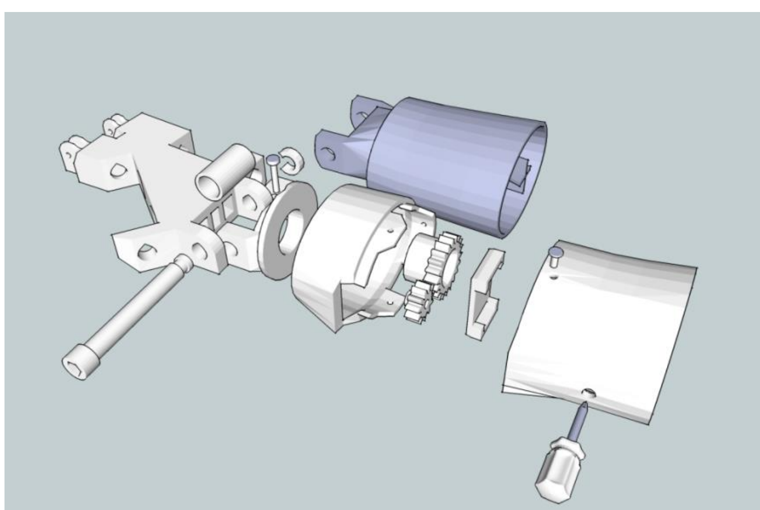


Figure 5.4.2-1: Wrist Module

5.4.3. Forearm

The forearm is composed of 7 STL files, of which each STL files contain one or more components are listed within. The leftrobcableback file contains only one component for structure support of the forearm. The leftrobcablefront file contains only one component for structure support of forearm. The leftrobservobed file contains only one component which will be housing 5 servo motors and structure support of forearm. The robring file contains 5 components that are to be attached to the servo motor disc. The lefttensioner file contains only one component which will provide tensioning capability for tuning. The leftrobpart3 is a file that contains only one component that serves as the cover for upper forearm. The robpart4 file contains only one component that serves as the cover for the lower forearm.

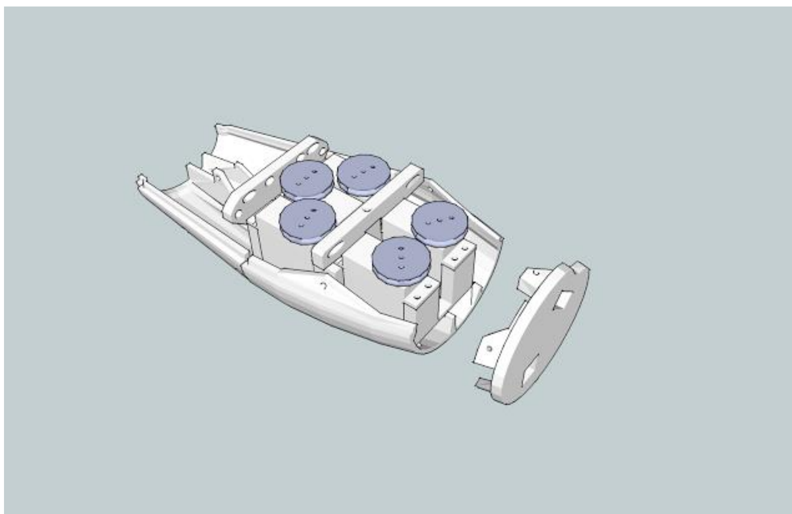


Figure 5.4.3-1: Forearm Module

5.4.4. Bicep

The bicep is composed of 22 STL files. The gearholder file contains only one component that holds the gears in place. The higharmside file contains only one component that provides structure support for the bicep. The pistonanticlock file contains only one component that is going to be mounted to the servo motor disc. The pistonbaseanti file contains only one component that is going to serve the purpose of helping bicep rotate. The rotgear file contains only one component that is going to serve the purpose of helping the elbow rotate. The rotmit file contains only one component that serve as structure support for rotation. The rotpotentio file contains only one component that serves as potentiometer holder. The rottit file contains only one component that serves as structure support for rotation. The rotworm file contains only one component that is going to be mounted to a servo motor disc. The rotcenter file contains only one component that serves as structure support for rotation. The armtopcover file contains only one component that serves as cover for the bicep. The armtopcover2 file contains only one component that serves as cover for the bicep. The armtopcover3 file contains only one component that serves as cover for the bicep. The elboshaftgear file contains only one component that serves as structure support for elbow rotation. The gearpotentio file contains only one component that serves as potentiometer holder. The leftrottit file contains only one component that serves as structure support for rotation. The leftrotceter file contains only one component that serves as structure support for rotation. The lowarmside file contains only one component that serves as structure support for the bicep. The reinforcer file contains only one component that serves as structure support for the bicep. The servobase file contains only one component that serves as servo mount. The servoholder file contains only one component that serves as servo mount. The spacer file contains only one component that serves as spacer.

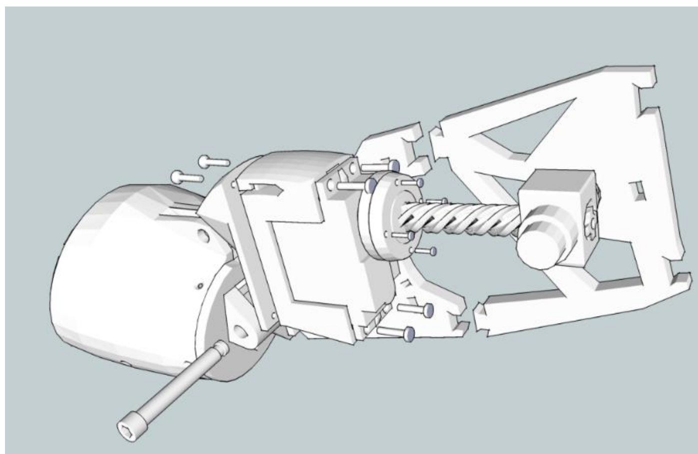


Figure 5.4.4-1: Bicep Module

5.4.5. Final Hand Design

Through the generous sponsorship of Hewlett-Packard Inc., HP, a robotic hand was loan and to be use for this project. Instead of a 3D-printed mechanical system, the new mechanical system is custom built by HP in house. The hand was constructed based on a 3D scan model of a real hand. The hand have individual movement capability for each of its fingers and thumb. Each fingers is manipulated by a micro metal gear servo in a pulley system using metal braided wire. The thumb is manipulated with a standard servo in a pulley system using mental braided wire.

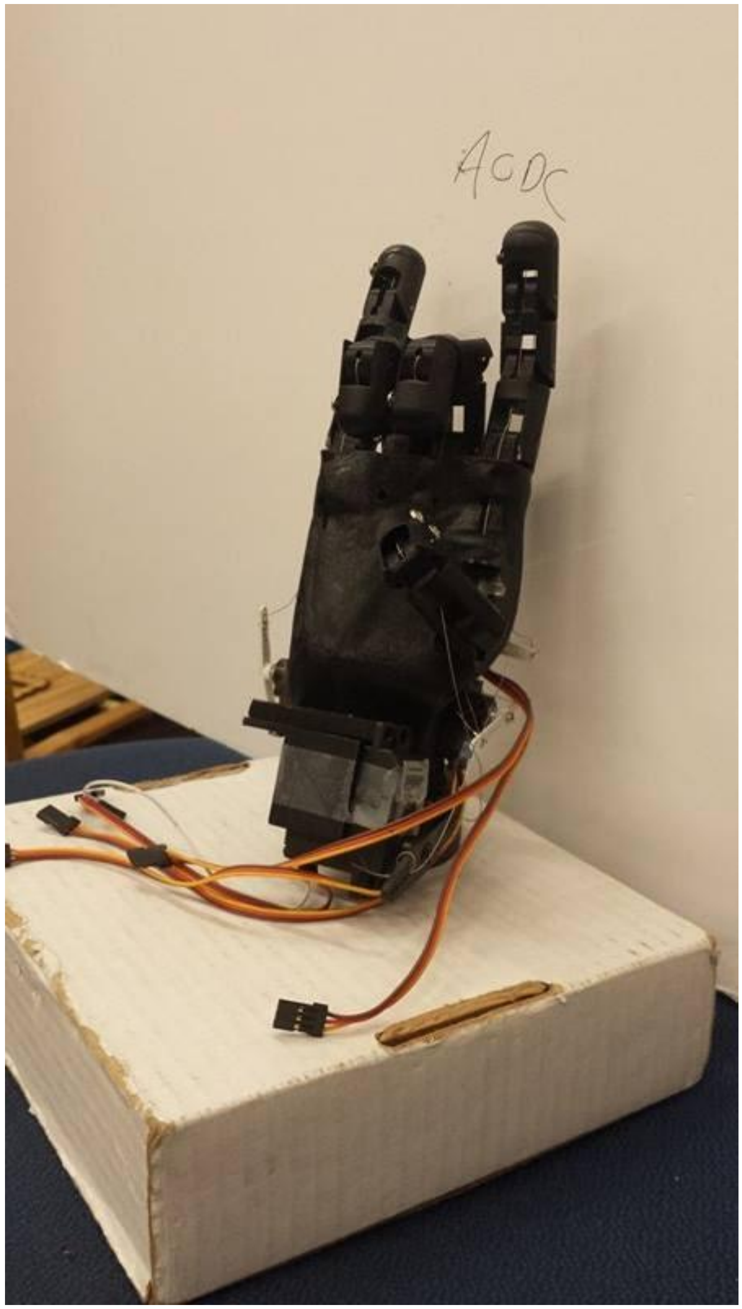


Figure 5.4.5-1: Final Hand Design

5.4.6. Final Arm Design

Through the generous sponsorship of Hewlett-Packard Inc., HP, a robotic arm was loan and to be use for this project. Instead of a 3D-printed mechanical system, the new mechanical system is custom built by HP in house. The arm has capability for 5 degrees of freedom, but for this project only 4 of the 5 degrees of freedom would be utilized. The degrees of freedom of the interest are one of the two shoulder joints, the elbow, forearm, and the wrist. Each degree of freedom are achieved through the usage of 24 V brushed DC motor fitted with reduction gear, which reduced the revolution and increase the torque capability of the motor. The feedback of each motor is provided by the rotary encoder sensor that is integrated on the rear of each of them.

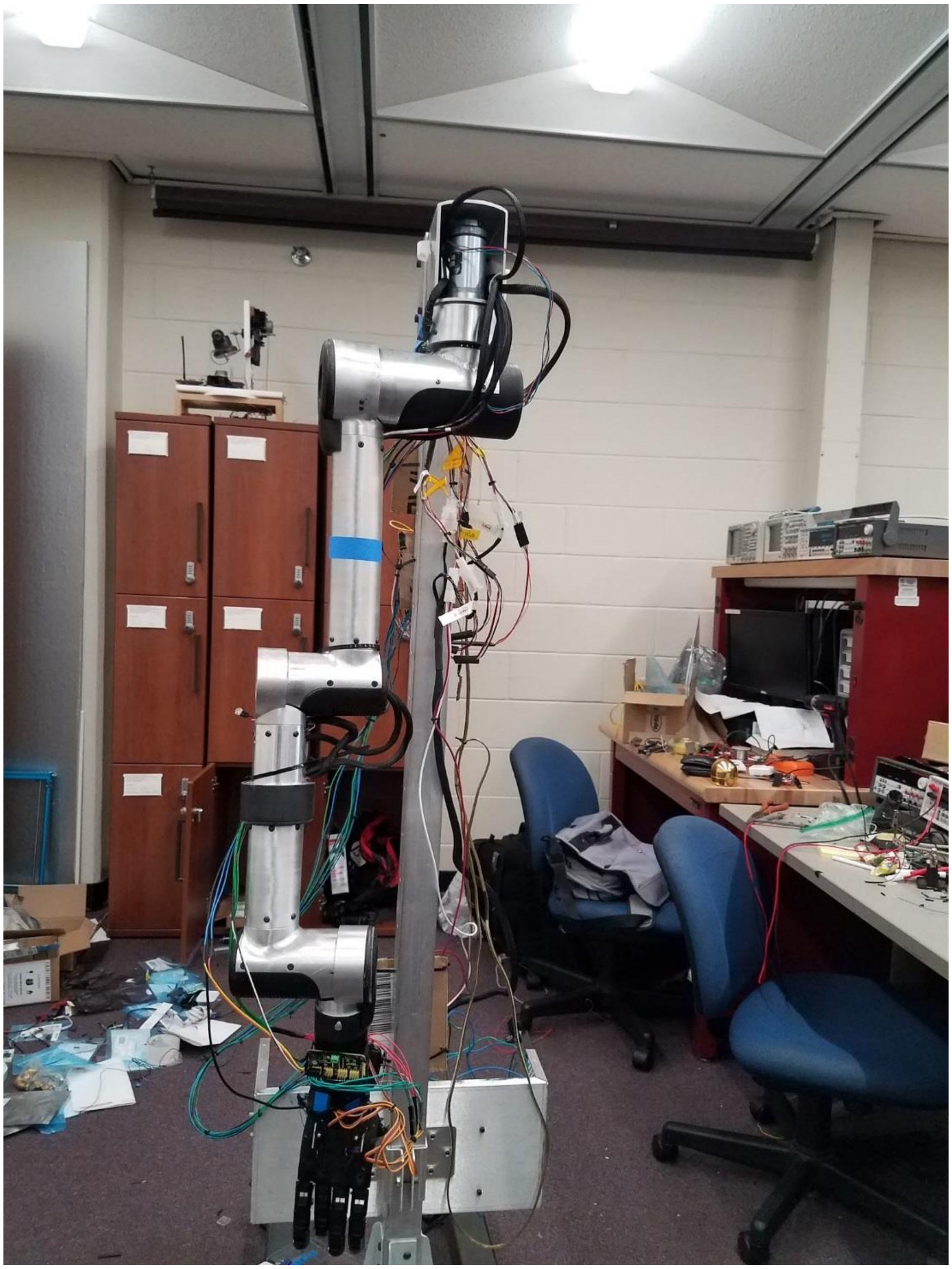


Figure 5.4.6-1: Final Arm Design

5.5. Power Validation

When testing the power for the project, it must be known that each power subsystem works on its own. Only then can the power be tested on a system level. The tests described here will included both subsystem and system level testing.

5.5.1. Subsystem Level Validation

This section is used for testing of the each of the subsystems, or mainly the voltage regulator circuits. These circuits need to be tested and verified that they work before being used at a system level.

5.5.1.1. Low Power Voltage Regulators

Purpose: The reason for this test is to ensure that all the low power systems in this project are receiving the correct loading conditions, to ensure that they receive both the correct currents and voltages. This test can be used for both the 3.3V regulator circuit for the digital components and the 5V regulator circuits for the sensors and communication.

Equipment:

- Voltage regulator circuit of interest
- DC power supply
- Multimeter
- Breadboard
- Load resistors

Preparation: Instead of using the DC battery, an independent DC power supply found usually in a lab will be used for these tests. Be sure that when using the either the 3.3V or the 5V regulator circuit that the appropriate load resistors are selected, as the loading conditions are different for each. This test is general for both regulator circuits.

Procedure:

1. Find loading condition for the respective regulator circuit.
2. Determine load resistor value based on loading condition.
3. Set up respective voltage regulator circuit on breadboard.
4. Apply DC voltage to input of regulator circuit, ensure that correct voltage is being inputted.
5. Using the multimeter, check the voltage across the load resistor and verify that it is the desired voltage.
6. If the voltage is correct, move to step 11; otherwise there is an issue that needs to be addressed so move to step 7.

7. Check that all components in the circuit have their correct respective values, replacing any incorrect or damaged components.
8. Check that all wiring is correct, replacing any wires that are damaged.
9. Check that the ICs are not damaged in any way, shape, or form, replacing any that are damaged.
10. Once all troubleshooting is completed, move back to step 4. If problems still persist, consider replacing entire circuit, changing power supplies, or moving to a different testing station altogether.
11. Once the voltage has been verified, the circuit must be tested for reliability and maintainability: leave the circuit running and monitor the voltage for at least 5 to 10 minutes, ensuring that the voltage regulation is reliable over time.

This test is crucial for the power distribution of this project because if the components in the system are not receiving proper loading, it may cause issues in performance or the system may not work at all. If there are no problems, or all problems have been fixed, during the testing procedure this test can reliably say that the circuit is in working order and usable in practice.

5.5.1.2. High Power Voltage Regulators

Purpose: The reason for this test is to ensure that the high power system providing loading to the motors are receiving the correct loading conditions, to ensure that they receive both the correct currents and voltages. This test is used for the 6V regulator circuit that outputs to the servo motors that will move the arm.

Equipment:

- 6V voltage regulator circuit
- DC power supply
- Multimeter
- Breadboard
- Load resistors that can handle high current

Preparation: Instead of using the power supply selected, an independent DC power supply found usually in a lab will be used for these tests. Note that for this test, the voltage regulator circuit will output to only one of the servos. This is to ensure that at least one servo works properly, so if one is properly loaded the other can be assumed to as well. This test also assumes that the servo will be at worst case scenario and be at maximum amperage at its specified voltage. If a high current resistor cannot be found, multiple resistors in parallel can be used to simulate one resistor.

Procedure:

1. Find a resistor that can handle up to 2.5 amps, refer to preparation should one not be available.
2. Set up 6V regulator circuit on breadboard.
3. Apply DC voltage to input of regulator circuit, ensure that correct voltage is being inputted.
4. Using the multimeter, check the voltage across the load resistor and verify that it is the correct voltage, is constant, and not fluctuating.
5. Using the multimeter, check the current flowing through the load resistor and verify it is constant and not fluctuating. Should multiple resistors be used, check the current flowing through each resistor and total each current.
6. If the loading conditions are correct, move to step 11; otherwise there is an issue that needs to be addressed so move to step 7.
7. Check that all components in the circuit have their correct respective values, replacing any incorrect or damaged components.
8. Check that all wiring is correct, replacing any wires that are damaged.
9. Check that the ICs are not damaged in any way, shape, or form, replacing any that are damaged.
10. Once all troubleshooting is completed, move back to step 4. If problems still persist, consider replacing entire circuit, changing power supplies, or moving to a different testing station altogether.
11. Once the voltage and current have been verified, the circuit must be tested for reliability and maintainability: leave the circuit running and monitor the voltage and current for at least 5 to 10 minutes, ensuring that the voltage regulation and output current are reliable over time.

This test is crucial for the power distribution of this project because if the components in the system are not receiving proper loading, it may cause issues in performance or the system may not work at all. This circuit in particular is important because it provides power to the servo motors, which does the heavy lifting and provides movement of the arm. Without it, the arm would not function properly. If there are no problems, or all problems have been fixed, during the testing procedure this test can reliably say that the circuit is in working order and usable in practice.

5.5.2. System Level Validation

This section is used for testing of the each of the subsystems integrated together. Once the subsystems have been verified that they work properly, only then can the power distribution can be tested altogether.

5.5.2.1. Glove/Sleeve Power Validation

Purpose: The reason for this test is to ensure that all the power distribution systems work properly when integrated together. For the sleeve system, this includes both the 3.3V and 5V regulator circuits. For reference on how these circuits integrate together, reference the design section of this document.

Equipment:

- 3.3V voltage regulator circuit
- 5V voltage regulator circuit
- DC power supply
- DC battery selected
- Multimeter
- Breadboard
- Load resistors

Preparation: Before using the DC battery, an independent DC power supply found usually in a lab will be used to test the whole integrated system before using the battery. For reference on how to integrate the regulator circuits together, refer to the design section.

Procedure:

1. Find loading conditions for each of the respective regulator circuits.
2. Determine load resistor values based on loading conditions for each circuit.
3. Set up each voltage regulator circuit on breadboard.
4. Apply DC voltage to input of the 5V regulator circuit, ensure that correct voltage is being inputted.
5. Using the multimeter, check the voltage of the input of the 3.3V regulator, the load resistor simulating the communication module, and the load resistor simulating the sensors. Verify that it is the desired voltage.
6. If the voltages are correct, move to step 7; otherwise there is an issue that needs to be addressed so move to step 9.
7. Using the multimeter, check the voltage to the load resistor(s) simulating the digital components of the system.
8. If the voltage(s) are correct, move to step 12; otherwise there is an issue that needs to be addressed so move to step 9.
9. Check that all components in the circuit have their correct respective values, replacing any incorrect or damaged components.
10. Check that all wiring is correct, replacing any wires that are damaged.
11. Check that the ICs are not damaged in any way, shape, or form, replacing any that are damaged.

12. Once all troubleshooting is completed, move back to step 5. If problems still persist, consider replacing entire circuit, changing power supplies, or moving to a different testing station altogether.
13. Once the voltage has been verified, the circuit must be tested for reliability and maintainability: leave the circuit running and monitor the voltage for at least 5 to 10 minutes, ensuring that the voltage regulation is reliable over time.
14. Once the reliability has been established, remove the DC power supply used to power this system and in its place use the DC battery selected in the design section.
15. Repeat steps 4-8 once. Once completed the test is over.

5.5.2.2. Arm Power Validation

Purpose: The reason for this test is to ensure that all the power distribution systems work properly when integrated together. For the arm system, this includes both the 3.3V, 5V, and 6V regulator circuits. For reference on how these circuits integrate together, reference the design section of this document.

Equipment:

- 3.3V voltage regulator circuit
- 5V voltage regulator circuit
- 6V voltage regulator circuit
- DC power supply
- Power supply selected
- Multimeter
- Breadboard
- Load resistors
- Load resistors that can handle high current

Preparation: Before using the power supply selected, an independent DC power supply found usually in a lab will be used to test the whole integrated system before using the power supply. Note that for this test, the voltage regulator circuit will output to only one of the servos. This is to ensure that at least one servo works properly, so if one is properly loaded the other can be assumed to as well. This test also assumes that the servo will be at worst case scenario and be at maximum amperage at its specified voltage. Should high current resistor be unavailable for this test, using resistors in parallel to simulate said load resistor is acceptable. For reference on how to integrate the regulator circuits together, refer to the design section.

Procedure:

1. Find loading conditions for each of the respective regulator circuits.
2. Determine load resistor values based on loading conditions for each circuit.

3. Set up each voltage regulator circuit on breadboard.
4. Find a resistor that can handle up to 2.5 amps, refer to preparation should one not be available.
5. Apply DC voltage to input of the 5V and 6V regulator circuits, ensure that correct voltage is being inputted.
6. Using the multimeter, check the voltage of the input of the 3.3V regulator, the load resistor simulating the communication module, the load resistor simulating the sensors, and the load resistor(s) simulating the servo motors. Verify that it is the desired voltage.
7. Using the multimeter, check the current flowing through the load resistor and verify it is constant and not fluctuating. Should multiple resistors be used, check the current flowing through each resistor and total each current.
8. If the voltages are correct, move to step 9; otherwise there is an issue that needs to be addressed so move to step 11.
9. Using the multimeter, check the voltage to the load resistor(s) simulating the digital components of the system.
10. If the voltage(s) are correct, move to step 15; otherwise there is an issue that needs to be addressed so move to step 11.
11. Check that all components in the circuit have their correct respective values, replacing any incorrect or damaged components.
12. Check that all wiring is correct, replacing any wires that are damaged.
13. Check that the ICs are not damaged in any way, shape, or form, replacing any that are damaged.
14. Once all troubleshooting is completed, move back to step 6. If problems still persist, consider replacing entire circuit, changing power supplies, or moving to a different testing station altogether.
15. Once the voltage has been verified, the circuit must be tested for reliability and maintainability: leave the circuit running and monitor the voltage for at least 5 to 10 minutes, ensuring that the voltage regulation is reliable over time.
16. Once the reliability has been established, remove the DC power supply used to power this system and in its place use the power supply selected in the design section.
17. Repeat steps 5-10 once. Once completed the test is over.

Should all tests be passed in these sections, the power distribution system has been deemed suitable for prototyping.

5.6. User Manual / Project Operations

The next few section discuss a detailed step through operation of the Helping Hand project.

5.6.1. Prerequisites

To fully operate this product, the following items and conditions are needed and must be met:

- Sleeve, equipped with electronics for motion sensing.
- Mechanical telerobotic arm for movement mimicking.
- LED Test circuit to ensure proper voltage for battery.
- Power supply unit.

5.6.2. Setting Up

To ensure proper functionality of the system, follow these setup procedures:

1. Plug each 7.4V ultra-thin battery into LED test circuit.
    a. If LED lights up, the battery is ready to use.
    b. If LED does not light up, charge the battery and test again.
2. Place 7.4V batteries back into sleeve electronics compartment.
3. Plug power supply unit into an available wall socket.
4. Make sure mechanical telerobotic arm is mounted properly.
5. Put on the sleeve, and calibrate the sleeve.

Once calibration is done, the arm is ready to be controlled.

5.6.3. Using the System

The sleeve is designed to take your kinematic readings and send them over to the arm where all computations are performed. Based off the speed in which you move your fingers, arm, and wrist and the positions of your fingers, arm, and wrist will be transmitted wirelessly to the arm. Real time calculations will be made and will control a driver for the servos to respond to your movements, in turn mimicking your movements.

When using the arm and sleeve, take note of the system’s limitations as designated in the design section of this document. Because of the complexity of the project and limitations of making more degrees of freedom, the arm will not respond to all movements.

After becoming adjusted to the arm, the arm is now suitable for any intended application.

5.7 Communication Update

The communication standard was changed from LoRa to the Bluetooth standard. The reason for this, is due to the nature of the project being changed between Senior Design 1 and 2. With this design change, there was a need to revise the communication standard that was needed. The requirements no longer required a large distance between the recording device and that of the arm, and it will now require a communication standard that can deliver information at a much faster rate, thus Bluetooth was chosen.

The modules that was used were the HC-05 and HC-06. The HC-05 was set up to be a master device that will receive all information from the HC-06, which then will processes said information for the arm. The HC-06 was used as a slave device that was embedded onto the exoskeleton. This device recorded all of the user's movement and then sent that information to the master.

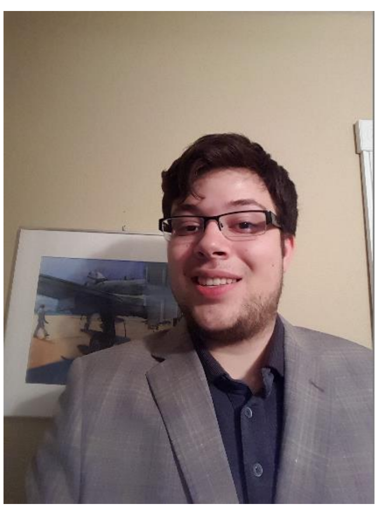
6. Administrative Content

Since this is a large and expensive project it is very important to make a detail finance budget as well as a well organize and realistic plan. This chapter discusses the tasks needed to complete this project, their projected completion time, and budget for materials and unexpected expenses.

6.1. Team Bios

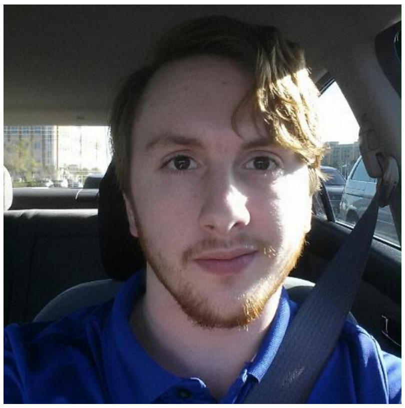
The following section discuss the biographies of the four students responsible for this project. This includes who they are as students, their accomplishments, and their future aspirations.

6.1.1. Carlos Cuesta



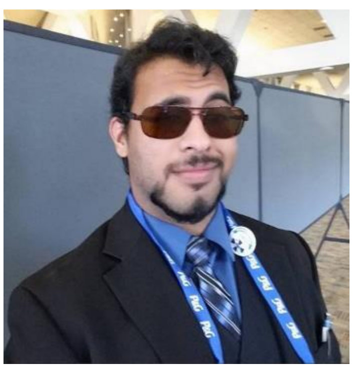
Carlos Cuesta is a senior undergraduate student at the University of Central Florida majoring in both Computer and Electrical Engineering, with focus on computer communication, software integration with its hardware counterpart, and embedded systems. He originally started as only a Computer Engineering student, but have always been fond of the hardware aspects of electrical machinery, and thus decided to add the Electrical Engineering program.

6.1.2. Devin Defond



Devin Defond is an undergraduate senior Electrical Engineering student here at University of Central Florida. He has interned as a PCB Networking Engineer at Lockheed Martin over the summer of 2015. He currently works as a Reliability, Maintainability, Testability, and Electrical Engineering CWEP at Lockheed Martin doing troubleshooting and testing of electrical systems for their Arrowhead program. After graduation, he aspires to continue on with his education with a Master’s (possibly Ph.D.) in power electronics.

6.1.3. Akash Jinandra



Akash Jinandra is undergraduate student at the University of Central Florida. He is majoring in Electrical and Computer Engineering. He is the chair of the IEEE undergraduate student branch at UCF. He has also done internships at Texas Instruments, Advanced Micro Devices, Precision Infinity, and Hewlett Packard. He hopes to get his Master’s degree and MBA in the future once he’s gotten more experience in the field.

6.1.4. Chang Chin Wu

Chang Ching Wu is a senior undergraduate student at the University of Central Florida majoring in Electrical Engineering, with focus on analog circuitry, hardware integration, and robotic systems. Attempting the Intelligent Robotic System minor with the focus on control of electromechanical system. Serve as the treasurer for the student branch of Institute of Electrical and Electronics Engineers at University of Central Florida throughout his undergraduate studies.

6.2. Team Breakdown

Akash Jinandra was responsible for overseeing the project's management. He also was responsible for the design of the sensor sleeve as well as the MCU interface for the Arm. This includes the build and prototype for the sleeve including both hardware and software design.

Devin Defond was responsible for the research and design of the power systems for the entire project. This includes the power systems of the arm and the power systems of the sleeve. This also includes the build and prototyping of the power systems.

Chang Ching Wu's primary responsibility for this project is the electromechanical system of the arm and sleeve. For the electromechanical system, he was in charge of the integrating servo motors with the mechanical mechanism of the humanoid robotic arm. Electrical circuit design for servo motor controller and sensors was required of him as well.

Carlos Cuesta primary responsibility for this project was the communications aspect. This included the research of communication modules and appropriate communications standards. This also included the design of the communication module and making sure that the arm and the sleeve are able to communicate without issue.

6.3. Project Milestones

The project milestones shown in Figure 6.3-1 allowed us to be a fully functioning team that had to meet deadlines set by the team itself. These deadlines allowed us to be able to provide research and design in a timely manner.

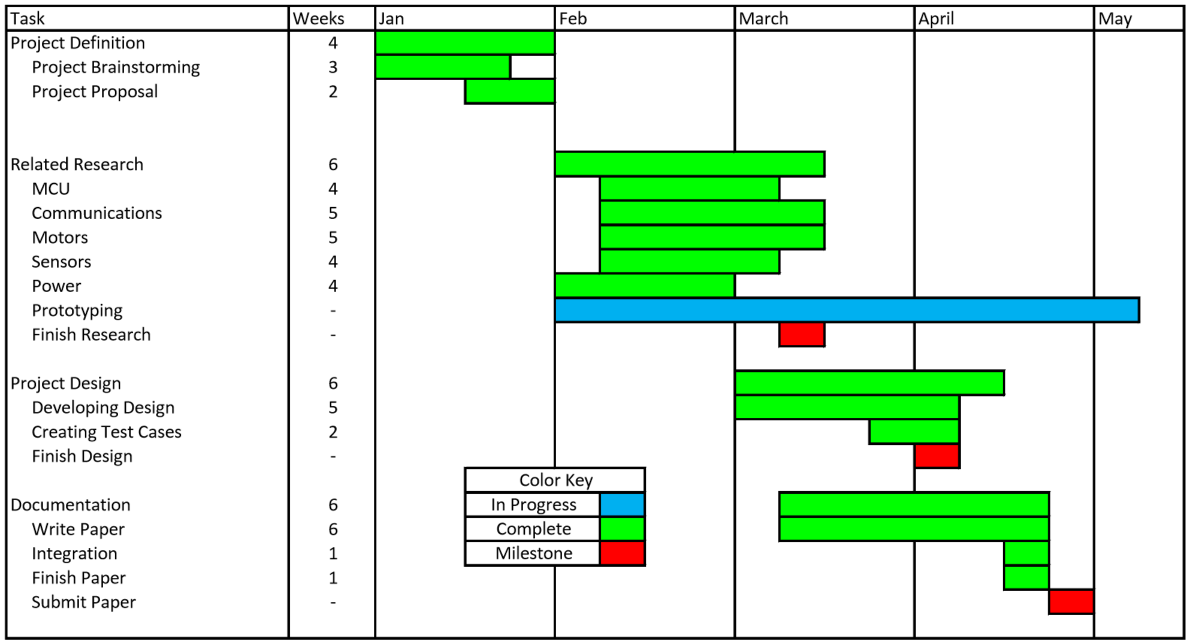


Figure 6.3-1: Team Milestones

6.4. Budget

This is the total bill for all of parts that are going to be required in order to build this project. All of the parts, the amount of each part, and their total price can be seen in table 6.4-1.

Item	#	Approx. Price	Overall Price
Exoskeleton	1	3D Printed	$1000
Mechanical Arm	1	$0	$20,000
Robotic Hand	1	$0	$200
Meanwell RSP 1500-24	1	$0	$316.90
Exoskeleton PCB	1	$20	$20
Arm Controller PCB	1	$20	$20
Exoskeleton Power PCB	1	$20	$20
Arm Power PCB	1	$20	$20
Atmega 328P	8	$24	$24
Atmega 16U2	2	$10	$10
Item	#	Approx. Price	Overall Price
LM317M	14	$13.16	$13.16
LP5907Q1-3.3	1	$0.67	$0.67
Bluetooth HC-05/06	2	$9.96	$9.96
MPU6050	1	$4.75	$4.75
Potentiometers	3	$1.65	$1.65
Encoders	2	$0	$66
Resistors	1	$15	$15
Capacitors	1	$50	$50
LED Pack	1	$5	$5
Zip ties	1	$12.50	$12.50
Wires Pack	1	$10	$10
Total		$236.69**	$21,819.59

Table 6.4-1: Budget

6.5. Conclusion

Power systems are integral to any project. Power systems are necessary as they allow the systems they power to work exactly as intended. Correct loading conditions provide for smooth operations of the system. Without the power systems providing power, nothing would work: the arm and the sleeve would not be able to communicate with each other, the sleeve would not get correct readings on arm and finger positions, and the arm itself would not be able to execute programs necessary to arm movement.

The reason why I picked to do communication section for this project is because I knew it would be a very important role in deciding whether the project will work or not. Without a proper foundation in the communication between the arm and the glove, nothing else would even matter, since the arm would just sit there not knowing what it needs to do. This however, is not the only reason why I chose to do the communication for this project. Another reason why I chose the section was that communication has always been a very interesting field in all things electronic. It has so many different objects that it impacts and for many of them it is one of, if not the, most important topic that any electronic device has to overcome.

In regards to the embedded system design, there were many things to take into consideration. When researching what microcontroller to use, it came down to two options, the MSP430 family of chips and the Atmel AVR's. It was decided to use the Atmega 328P, this is due to the overwhelming community support that is available online. There are numerous libraries that have been made the software easier to use. There is also lots of support also for hardware bootloading. The prototyping for the chip is also very simple, as you can use the Arduino Uno as an evaluation module. A useful aspect of using this chip is the chip can be taken directly off of the Arduino Uno and put on our PCB. This is helpful in the case where the chip can't be boot loaded separately.

The sensors were selected based on the hardware/software resources that are available for the user to utilize. The electromechanical interfere, servo motors, were selected based on their capability to provide the dynamic aspect for the mechanical system regarding the robotic arm. The PWM controller chip was selected for its capability of generating multiple channels of PWM through simple interface of I2C bus. The InMoov humanoid robotic arm was selected as the mechanical design, for its integration capability with electrical system.

As one can see, this paper encompasses everything involved in the completion of this senior design project. From the first to second semester, the group was given a sponsorship from Hewlett Packard Inc. They loaned us a robotic arm, robotic hand, stand, power supply and evaluation modules. In addition, they have guaranteed reimbursement for the other costs including PCB and exoskeleton construction. Due to this sponsorship the group did not use the InMoov arm, and used HP's arm. Also the group opted to change form a sleeve to a 3D printed exoskeleton to capture the user's motion. The groups mission was updated to mimic the human arm in as closely as possible using an exoskeleton instead of a sleeve. With an optional mission to change an HP LaserJet printer cartridge. The group enabled 4 degrees of freedom on the robotic arm: the shoulder, elbow, forearm and wrist. This was implemented through the processing PCB on the arm side.   The group used four PCB's, two power boards and two processing boards to complete the project. These boards were ordered from pcbway.com. This project taught the group how to work in a team with people of different backgrounds. Also how to work on a project with tight deadlines, and to do things that was never thought possible in the given time frame.

7. Appendices

These sections detail any references we used for research and design. All permissions are included as well.

7.1. References

http://inmoov.fr/

https://learn.sparkfun.com/tutorials/integrated-circuits/ic-packages

http://www.instructables.com/id/DIY-Robotic-Hand-Controlled-by-a-Glove-and-Arduino/

https://www.arduino.cc/en/Products/Compare

https://learn.adafruit.com/adafruit-arduino-selection-guide/arduino-comparison-chart

http://www.ti.com/lit/ug/slau356a/

Williams, B. W. (1992). "Chapter 11". Power electronics: devices, drivers and applications (2nd Ed.)

http://batteryuniversity.com/

http://www.digikey.com/en/articles/techzone/2012/may/understanding-the-advantages-and-disadvantages-of-linear-regulators

http://www.ece.ucf.edu/files/labs/EEL%204309%20Jan%202012.pdf

http://www.ece.ucf.edu/files/labs/EEE3307.pdf

https://learn.adafruit.com/li-ion-and-lipoly-batteries/protection-circuitry

http://www.ti.com/lit/an/snva559/snva559.pdf

http://www.ti.com/lsds/ti/analog/webench/overview.page?DCMP=analog_power_mr&HQS=webench-pr

"802.11ac Advances - Gigabit Wireless? Five 802.11ac Routers, Benchmarked." Tom's Hardware. 2013. Web. 28 Mar. 2016.

"How Far Can Wireless Work?" How Far Can Wireless Work? Web. 28 Mar. 2016.

Reiter, Gil. "Wireless Connectivity for the Internet of Things." One Size Does Not Fit All. Texas Instruments, 2014. Web. 20 Mar. 2016.

"Wireless B vs G vs N vs AC | What Is The Difference?" Best Wireless Routers. 2014. Web. 20 Mar. 2016.

"Wireless: 802.11b Wireless Protocol - GROK Knowledge Base." Wireless: 802.11b Wireless Protocol - GROK Knowledge Base. Web. 24 Mar. 2016.

"What Is LoRa? - Link Labs." Link Labs. 2015. Web. 27 Mar. 2016.

"Using Sub-gigahertz Wireless for Long Range Internet of Things Connectivity." Embedded. Web. 27 Mar. 2016.

"Extreme Range Links: LoRa 868 / 900MHz SX1272 Module for Arduino, Waspmote and Raspberry Pi." Extreme Range Links: LoRa 868 / 900MHz SX1272 Module for Arduino, Waspmote and Raspberry Pi. Web. 27 Feb. 2016.

"Sub-GHz Wireless Design Choices for Smart Metering." Wireless Design and Development. 2014. Web. 27 Feb. 2016.

http://www.usb.org/developers/whitepapers/327216.pdf
"Hear from the Micro:bit Creators." Bluetooth Technology Website. Web. 27 Mar. 2016.

"Information Age." The Bluetooth Blues. Web. 27 Mar. 2016.

Newton, Harold. (2007). Newton’s telecom dictionary. New York: Flatiron Publishing.

"802.11g WiFi (2.4GHz) vs. XPress Ethernet Bridge (900MHz)." Kb. Web. 22 Mar. 2016.

"DesignSpark." 11 Internet of Things (IoT) Protocols You Need to Know About ». Web. 27 Jan. 2016.

7.2. Permissions

BA BatteryU <BatteryU@cadex.com>

To: Devin Defond;

Reply all

Wed 2/24/2016 9:02 PM

Hi Devin,

Yes, you may use the material as requested. Please cite sources where appropriate.

Regards,

John Bradshaw - Marketing Communications Manager
Cadex Electronics Inc. | www.cadex.com
Vancouver | Minneapolis | Frankfurt
Tel: +1 604 231-7777 x319 | Toll Free: 1-800 565-5228

Follow us on Twitter: twitter.com/cadexelectronic
Join us on Facebook: facebook.com/cadexelectronics
Add us on Google+: plus.google.com/+Cadex

>>> Devin Defond <ddefond12@knights.ucf.edu> 2/23/2016 8:20 PM >>>

DD Devin Defond

To: batteryu@cadex.com <BatteryU@cadex.com>;

Wed 2/24/2016 4:20 AM

Hello,

My name is Devin Defond and I am a student and the University of Central Florida. I am currently in Senior Design and on behalf of my group, I am asking for permission to user your Alkaline AA Voltage versus Time graph for internal resistance for a paper we are writing for the class project.

I thank you and appreciate your time,
Devin Defond
Electrical Engineering Student
University of Central Florida
(941) 286-5326 | ddefond12@knights.ucf.edu

Alkaline Batteries: Permission Obtained

Digikey Permission to Publish

DD Devin Defond

Reply all

To: sales@digikey.com;

Thu 3/3/2016 12:18 AM

Hello,

My name is Devin Defond and I am a student and the University of Central Florida. I am currently in Senior Design and on behalf of my group, I am asking for permission to use your "Table 1: Comparison of the characteristics of switching and linear regulators" for a paper we are writing for the class project.

I thank you and appreciate your time,

Devin Defond
Electrical Engineering Student
University of Central Florida
(941) 286-5326 | ddefond12@knights.ucf.edu

Switching vs Linear Regulators: Permission Pending